Exploring the Solar System with Wide-Field Imaging from Space

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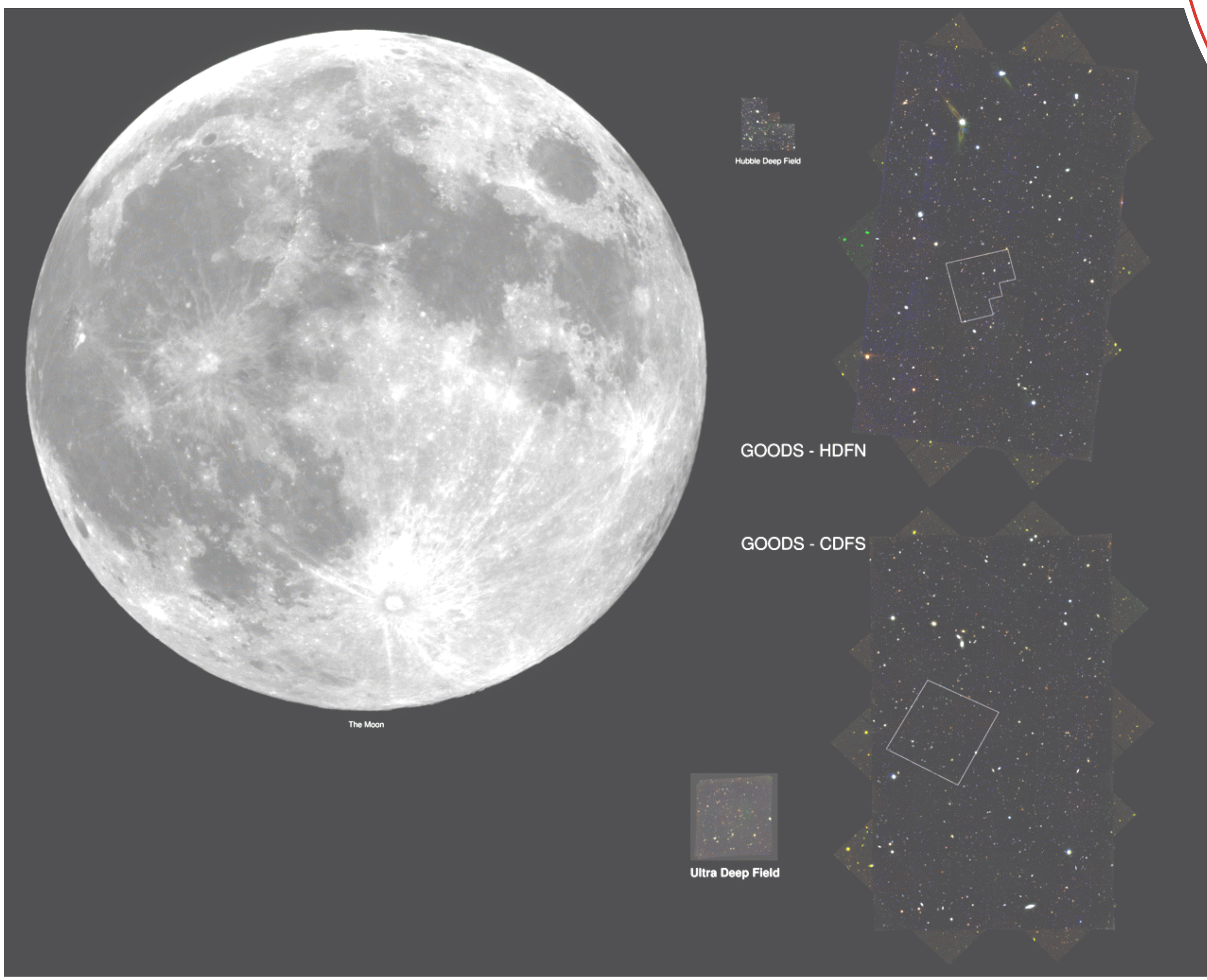
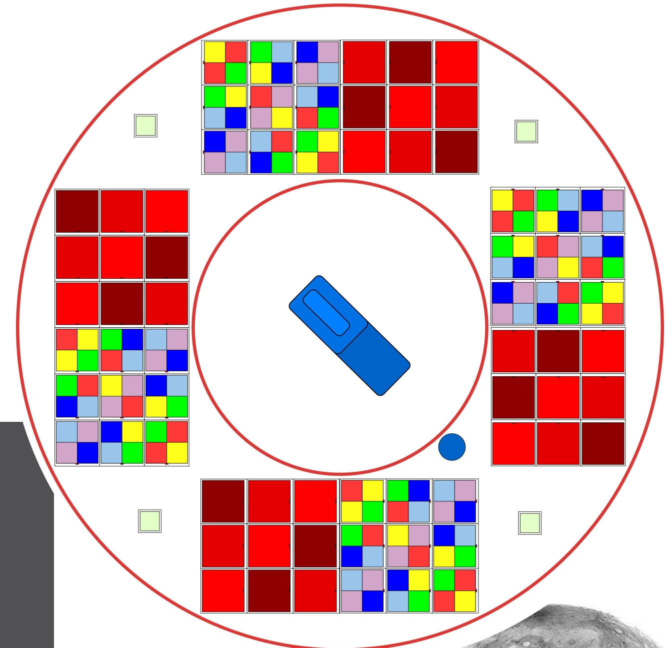
May 18, 2004

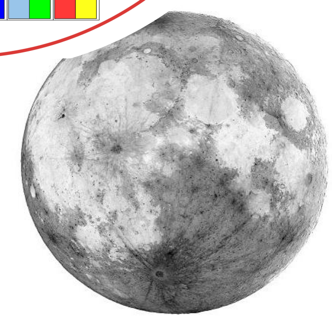
Solar System Frontiers
The Kuiper Belt: Laboratory of Planetary Accretion
Space-Borne Detection of Reflected Light
Space-Borne Occultation Surveys

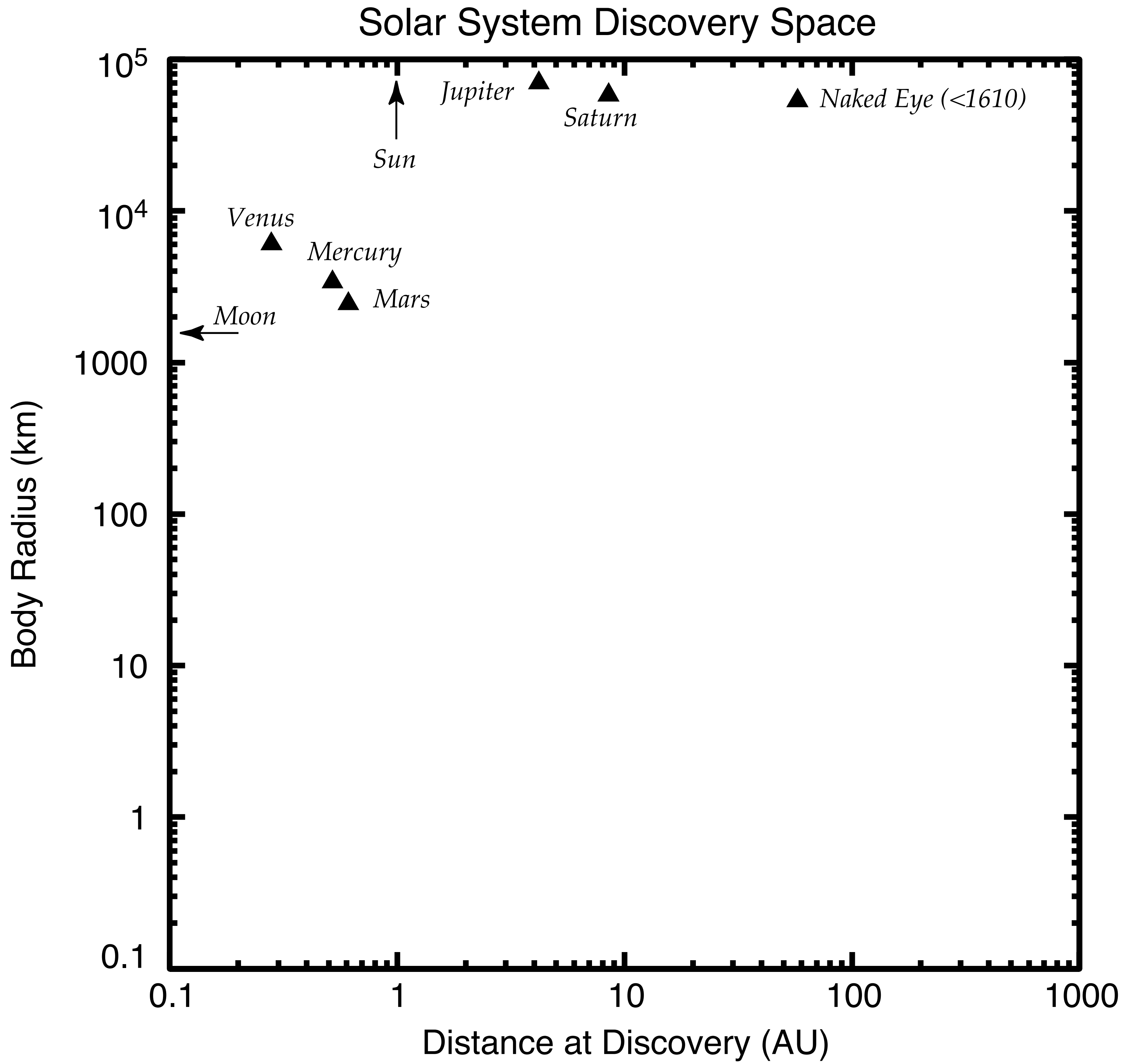
a bullet-free presentation (almost).

Solar System Priority #1: A Really Nice Image of the Full Moon?

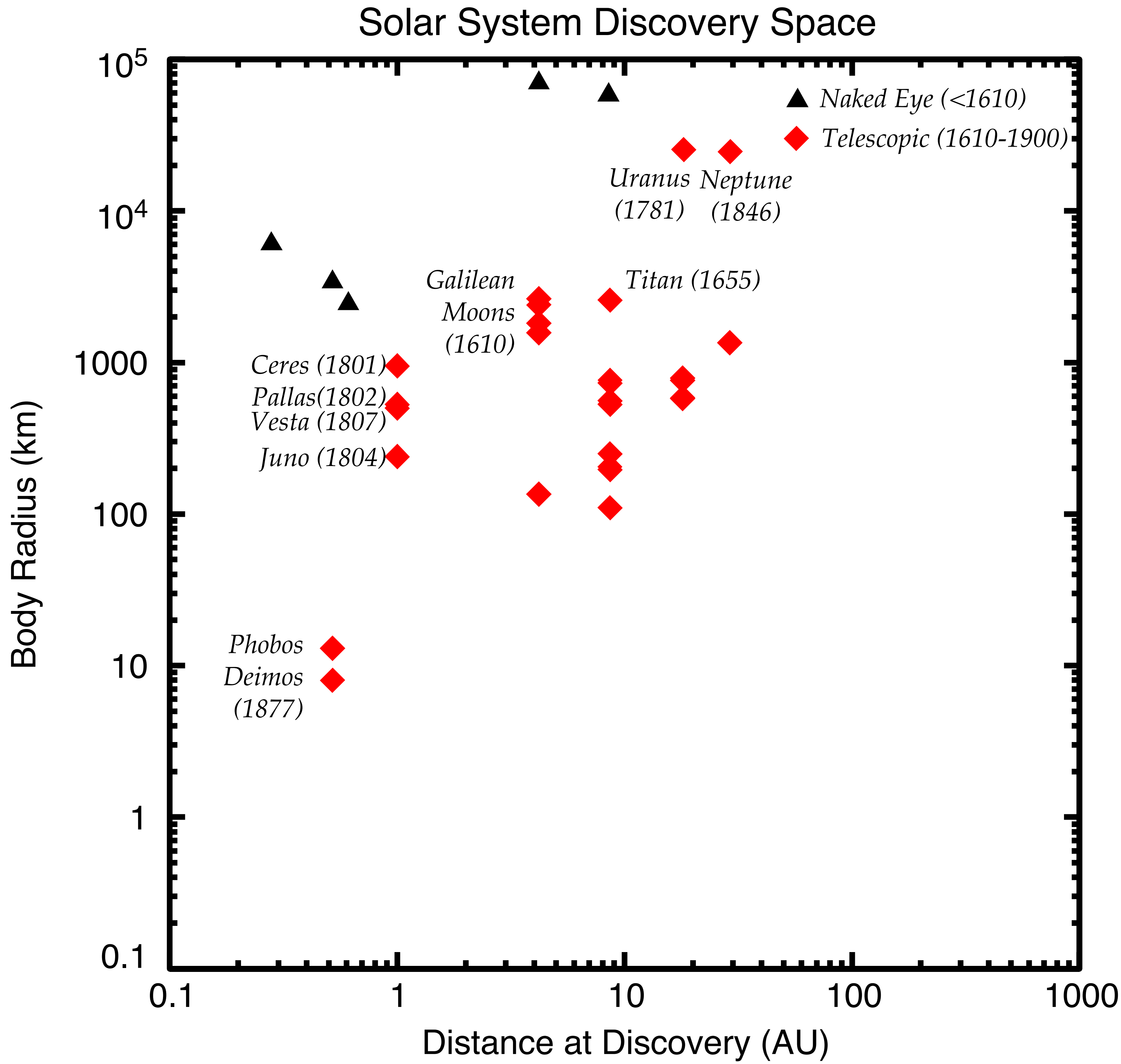




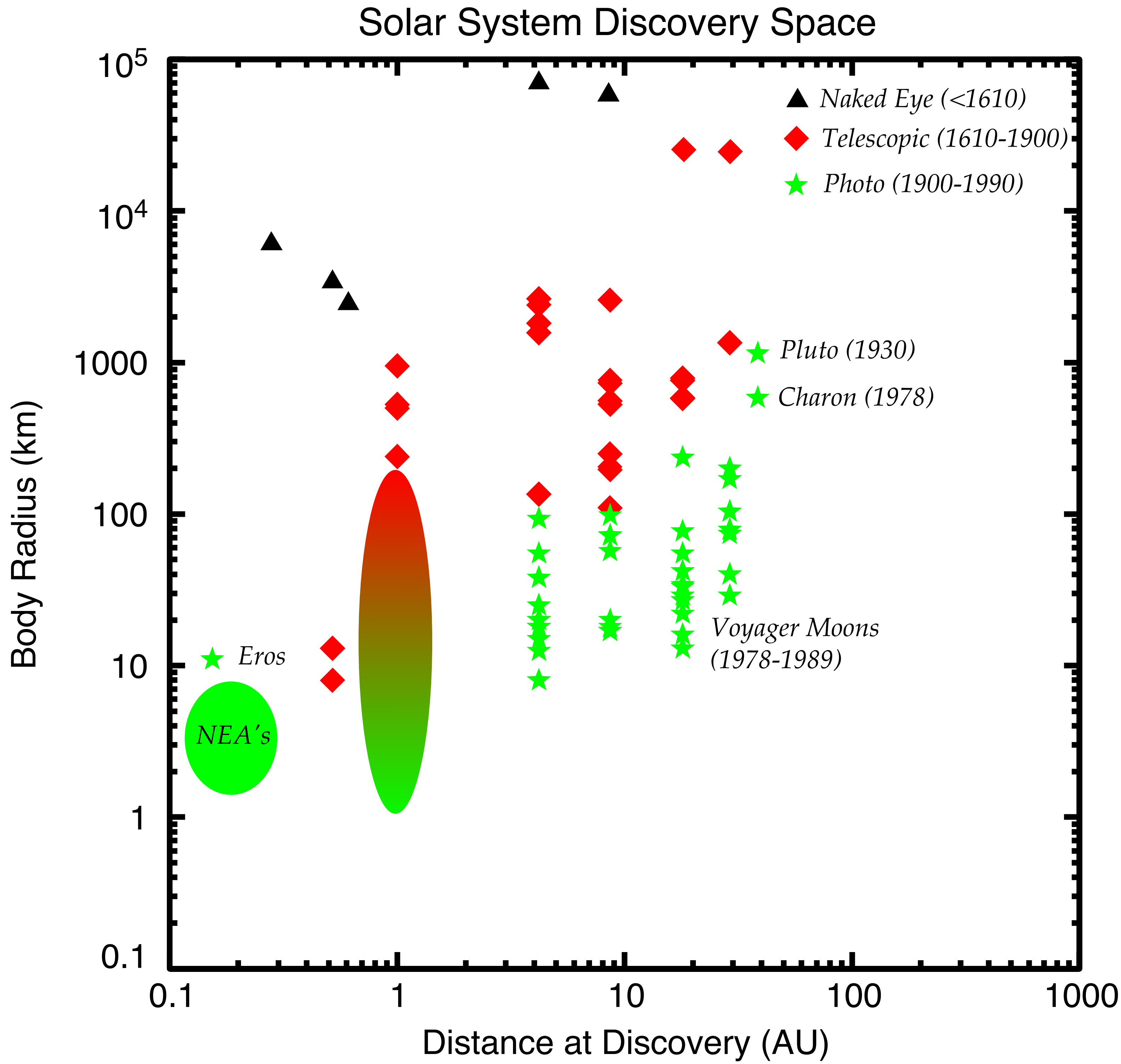




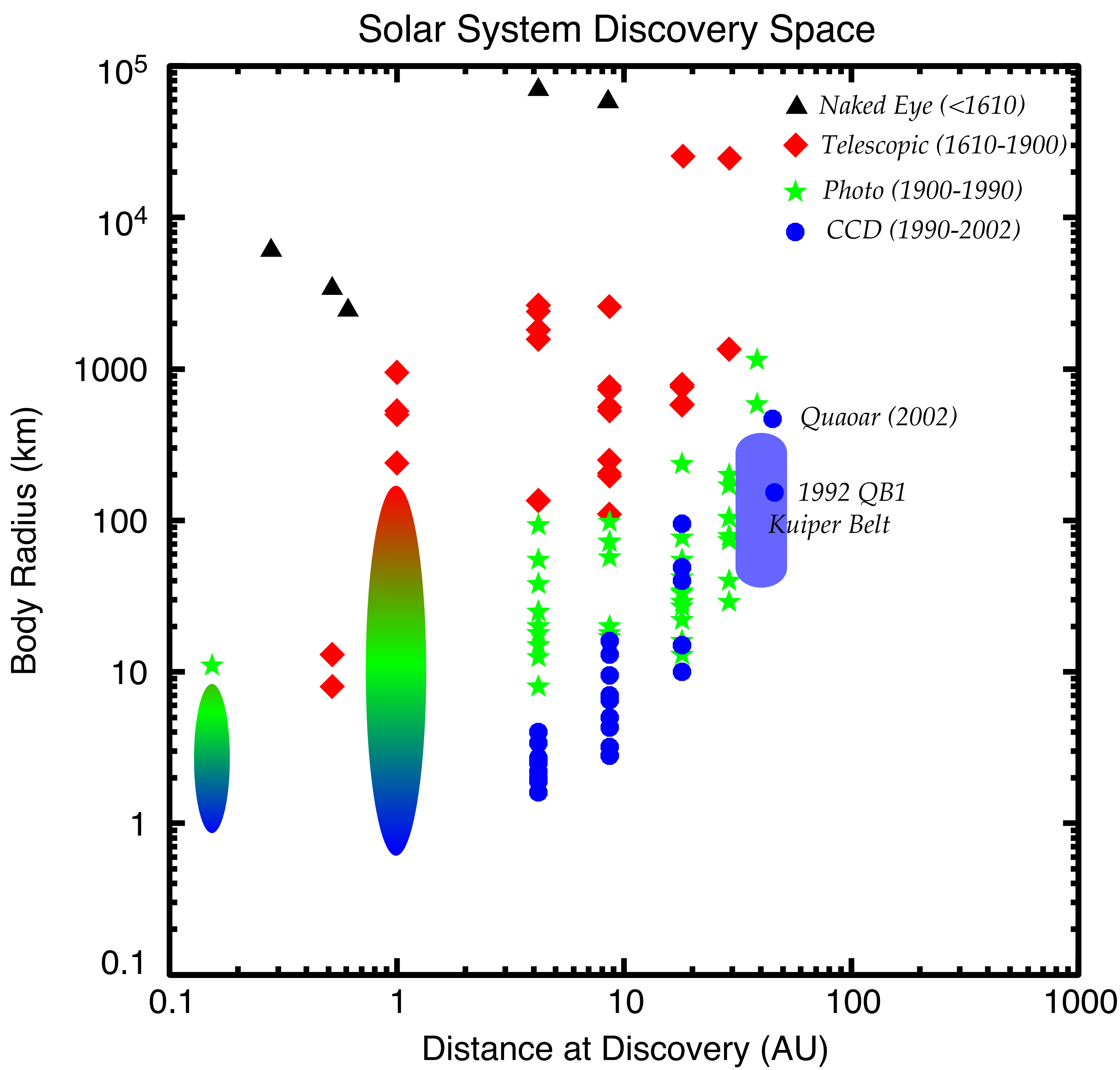
Solar System Discovery Space
Jupiter
Saturn
Naked Eye (<1610)
Sun
Venus
Mercury
Mars
Moon
Body Radius (km)
Distance at Discovery (AU)

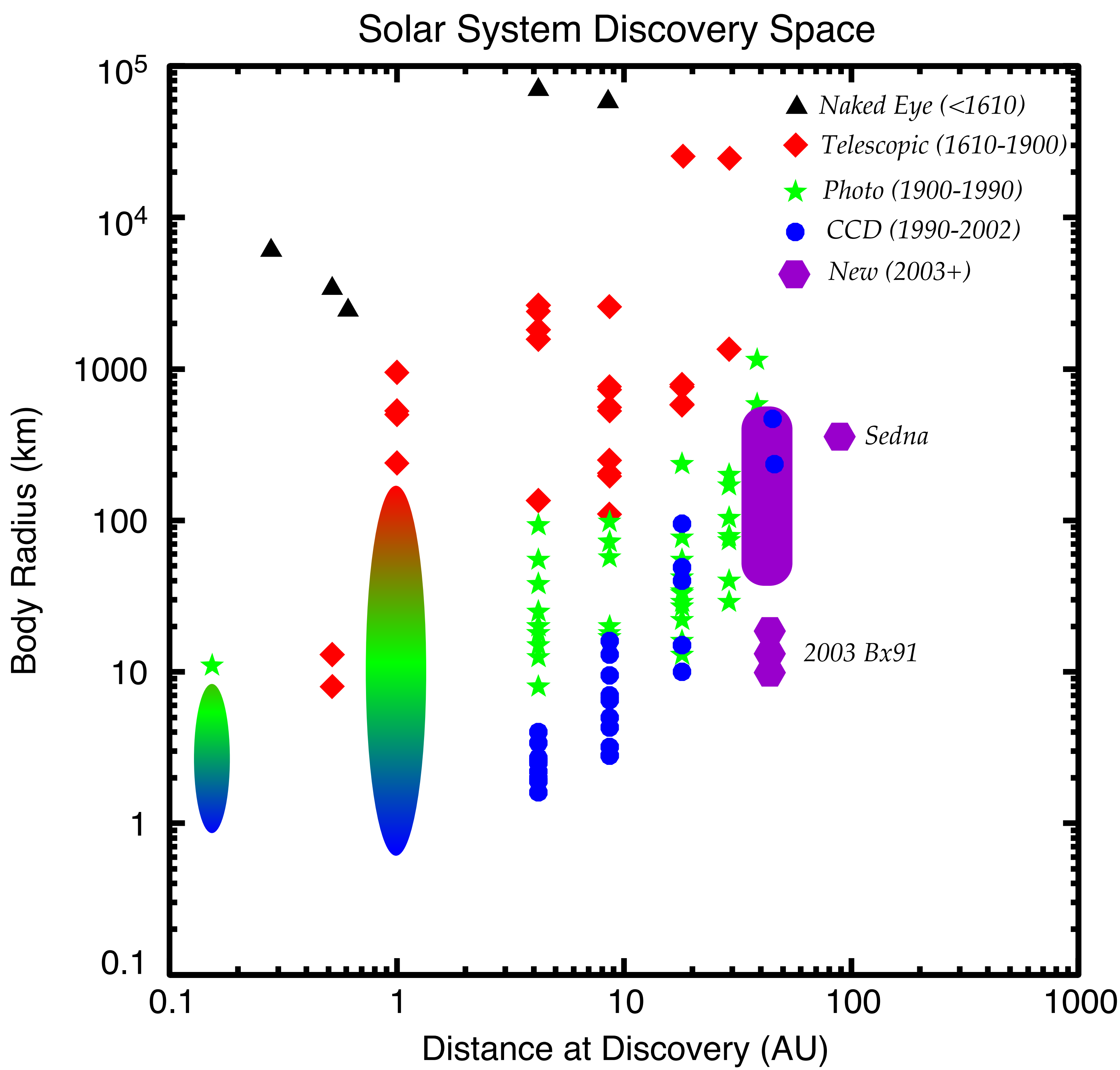


Solar System Discovery Space
Body Radius (km)
Distance at Discovery (AU)
0.1
1
10
100
1000
10^5
10^4
Naked Eye (<1610)
Telescopic (1610-1900)
Uranus (1781)
Neptune (1846)
Galilean Moons (1610)
Titan (1655)
Ceres (1801)
Pallas(1802)
Vesta (1807)
Juno (1804)
Phobos
Deimos
(1877)

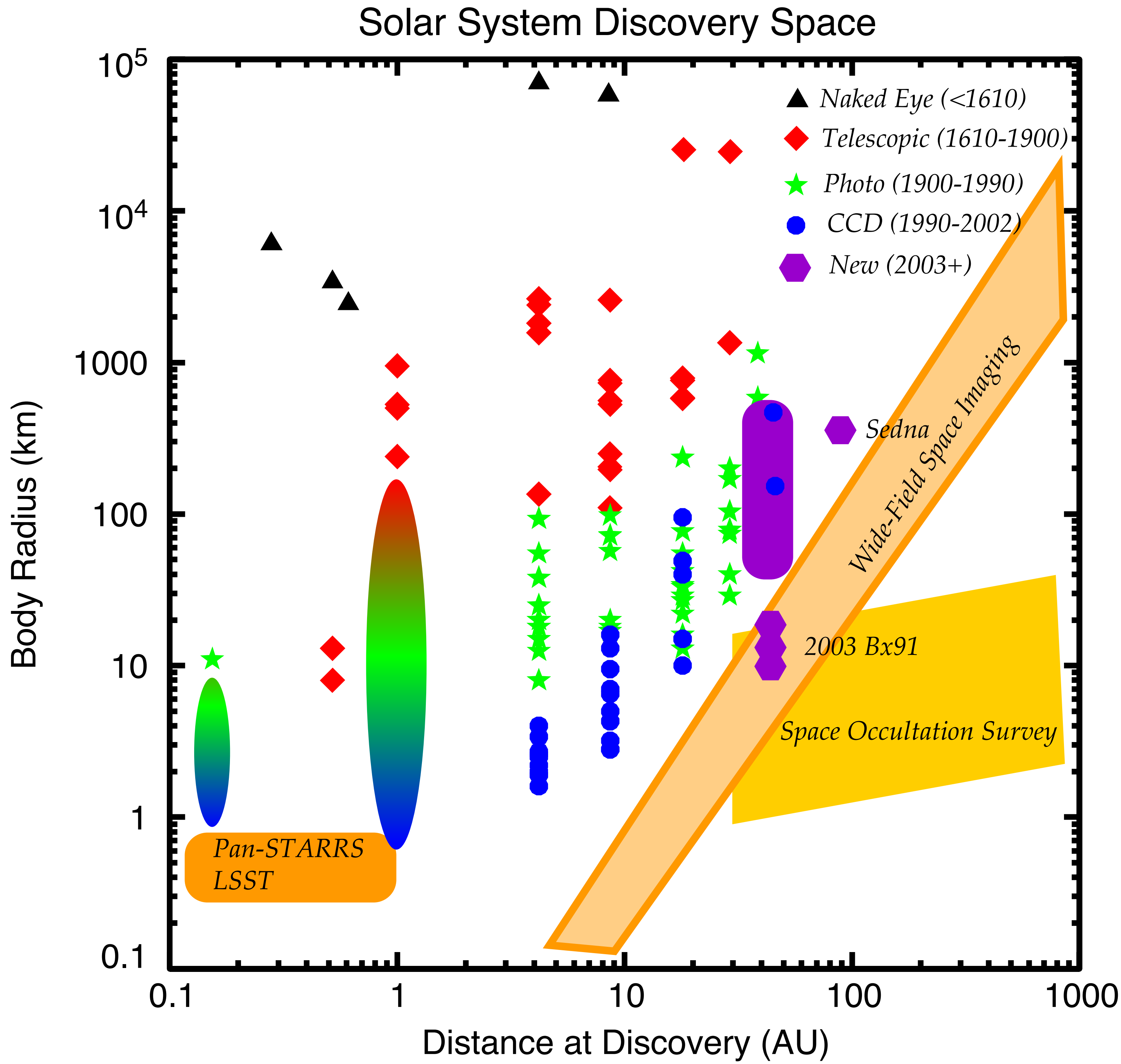


Solar System Discovery Space
Naked Eye (<1610)
Telescopic (1610-1900)
Photo (1900-1990)
Pluto (1930)
Charon (1978)
Voyager Moons
(1978-1989)
Eros
NEA's
Body Radius (km)
Distance at Discovery (AU)


Solar System Discovery Space
Body Radius (km)
Distance at Discovery (AU)
10^5
10^4
1000
100
10
1
0.1
0.1
1
10
100
1000
Naked Eye (<1610)
Telescopic (1610-1900)
Photo (1900-1990)
CCD (1990-2002)
Quaoar (2002)
1992 QB1
Kuiper Belt

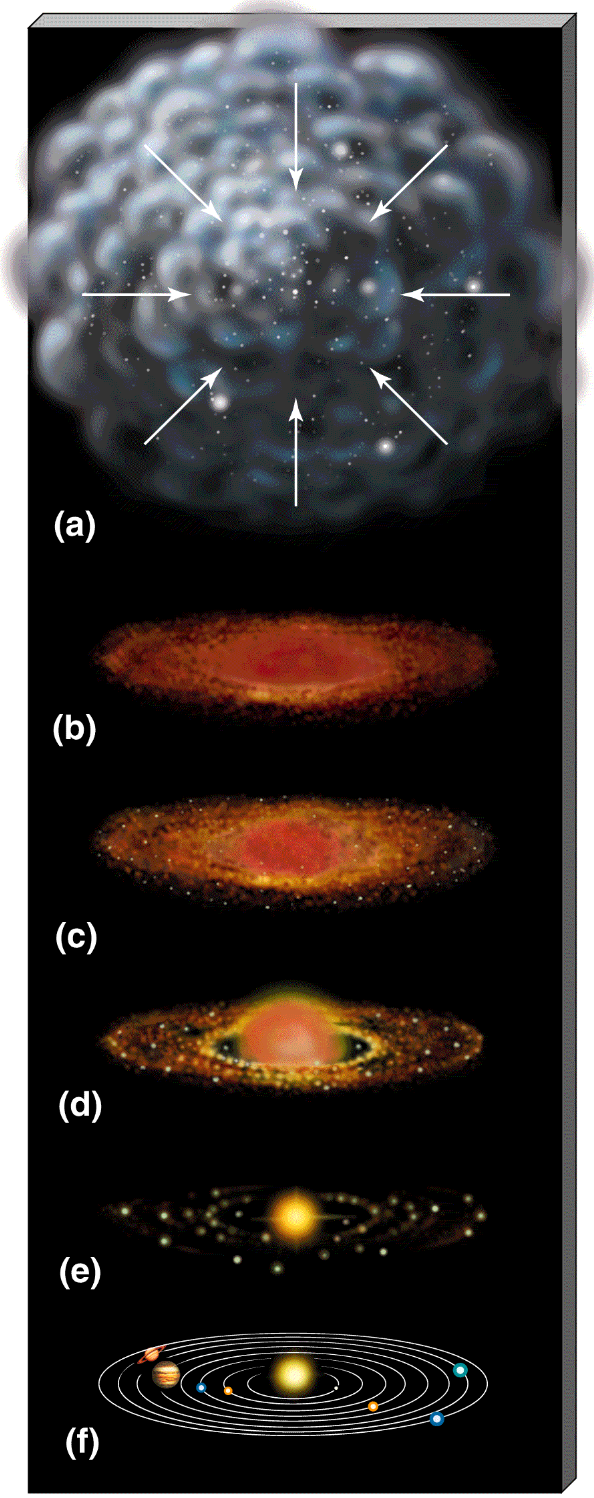


Solar System Discovery Space
Naked Eye (<1610)
Telescopic (1610-1900)
Photo (1900-1990)
CCD (1990-2002)
New (2003+)
Sedna
2003 Bx91
Body Radius (km)
Distance at Discovery (AU)
10^5
10^4
1000
100
10
1
0.1
0.1
1
10
100
1000



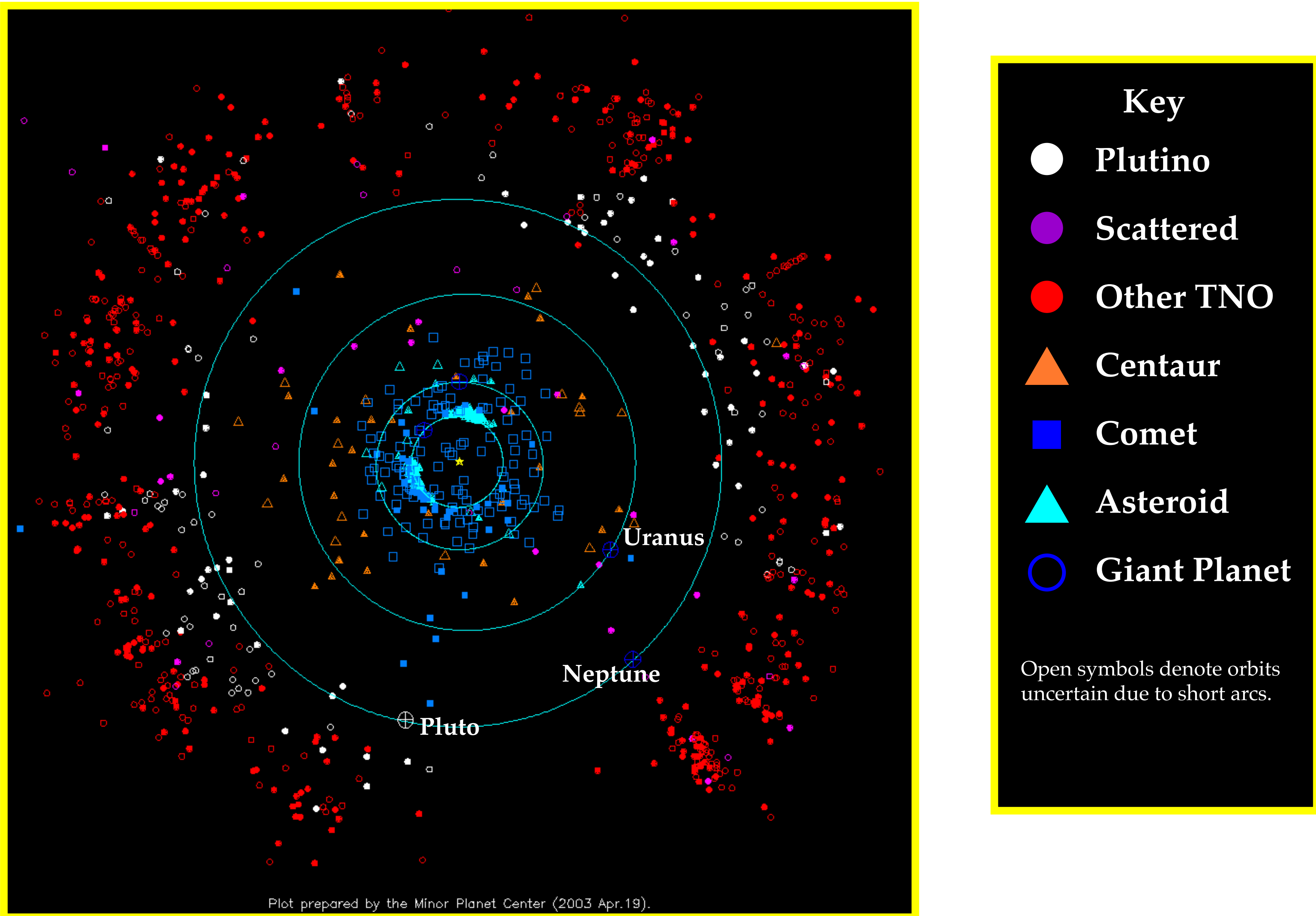
Solar System Discovery Space
Naked Eye (<1610)
Telescopic (1610-1900)
Photo (1900-1990)
CCD (1990-2002)
New (2003+)
Sedna
Wide-Field Space Imaging
2003 Bx91
Space Occultation Survey
Pan-STARRS
LSST
Body Radius (km)
10^5
10^4
1000
100
10
1
0.1
0.1
1
10
100
1000
Distance at Discovery (AU)

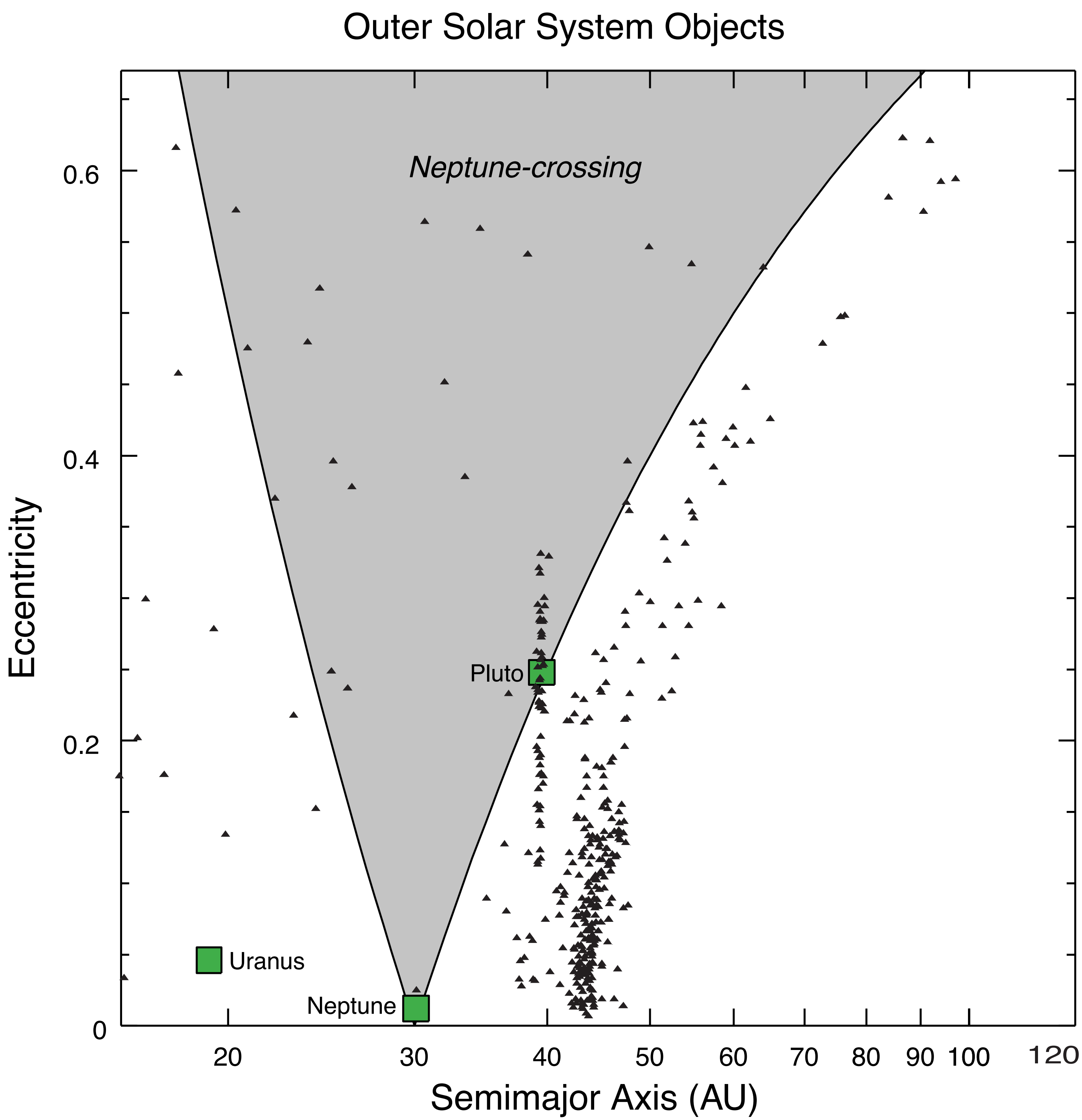
Planet Formation Scenario:



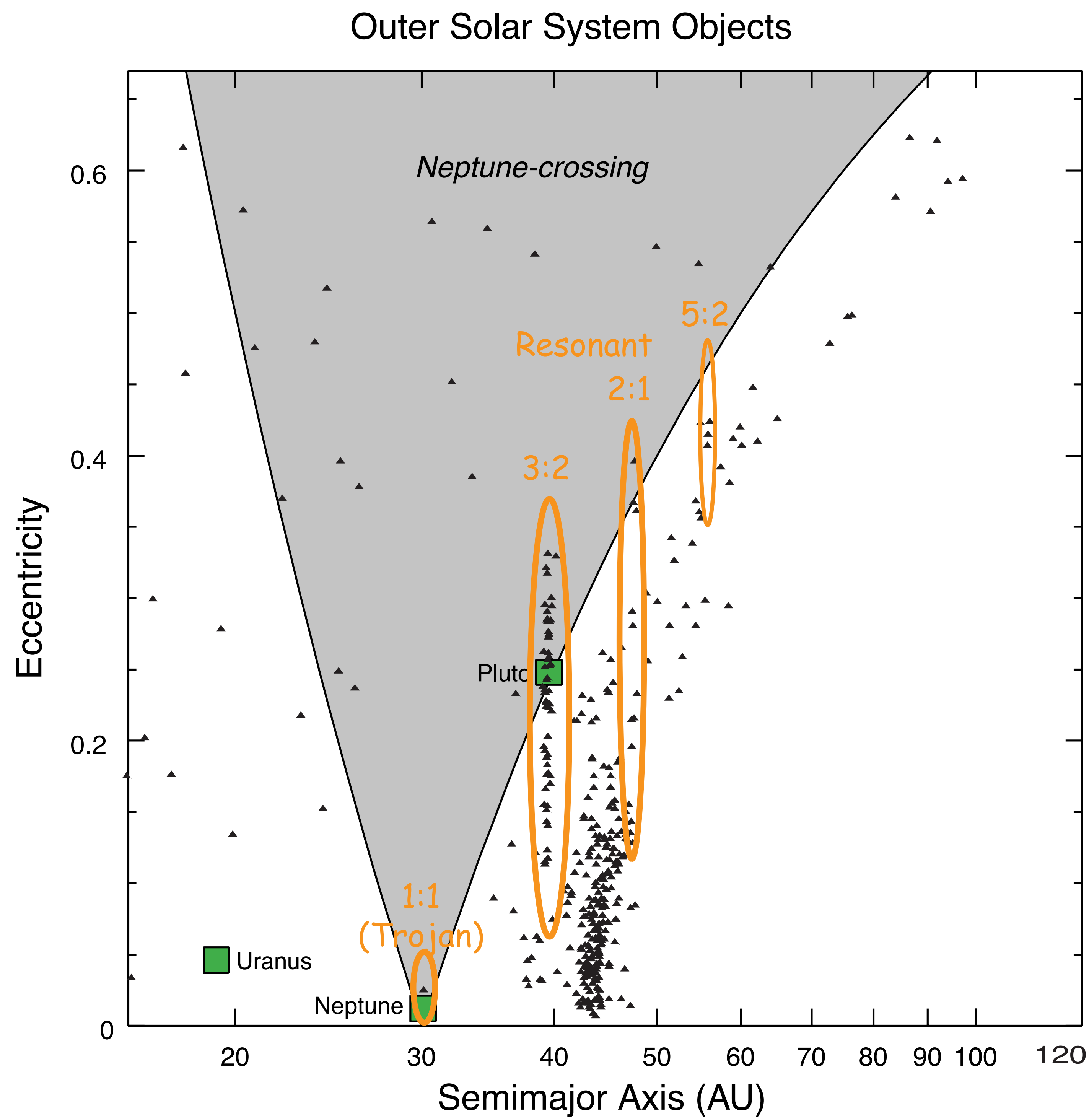
Theoretical Expectation:	*Observational Evidence:*
Collapse of gas/dust cloud to form protostar and nebular disk.	Nebular/dust phases are observed around other stars
Coagulation of grains, runaway gravitational growth of planetesimals	
Oligarchic growth of planetesimals.	Planetesimal phase is observable only in our outer "fossilized" Solar System - the Kuiper Belt.
Gas accretion onto largest bodies, dissipation of gas, ejection of small bodies	
Mature planetary system	Giant planets have been detected around other stars

Known Outer Solar-System Bodies (as of 2003 April 19)





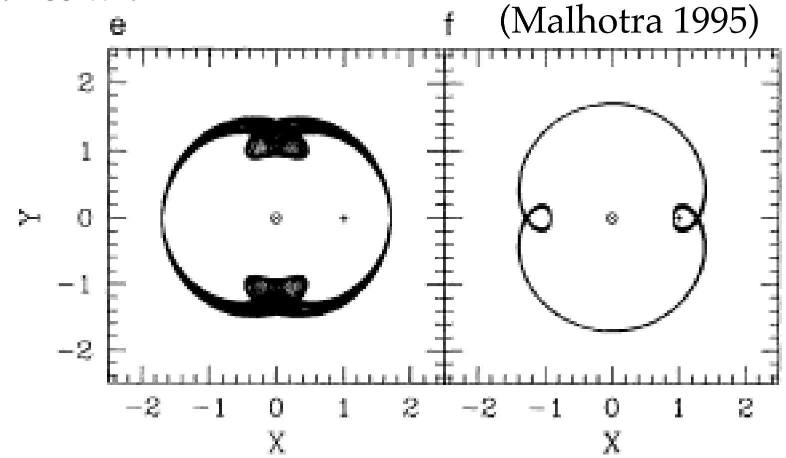
Outer Solar System Objects
Neptune-crossing
Pluto
Uranus
Neptune
Eccentricity
0
0.2
0.4
0.6
20
30
40
50
60
70
80
90
100
120
Semimajor Axis (AU)


Outer Solar System Objects
Neptune-crossing
Resonant
5:2
2:1
3:2
Pluto
1:1
(Trojan)
Uranus
Neptune
Eccentricity
0.6
0.4
0.2
0
20
30
40
50
60
70
80
90
100
120
Semimajor Axis (AU)

KBO Resonances and Planetary Migration

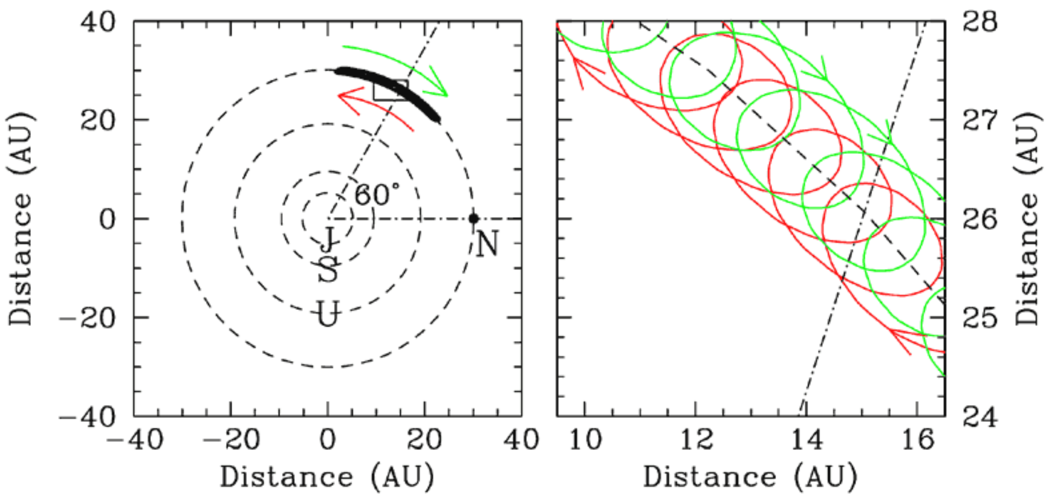
- Pluto and many KBOs ("Plutinos") are locked in 3:2 resonance with Neptune, crossing Neptune's orbit yet avoiding ejection.

3:2 Resonances in Neptune frame (Malhotra 1995)

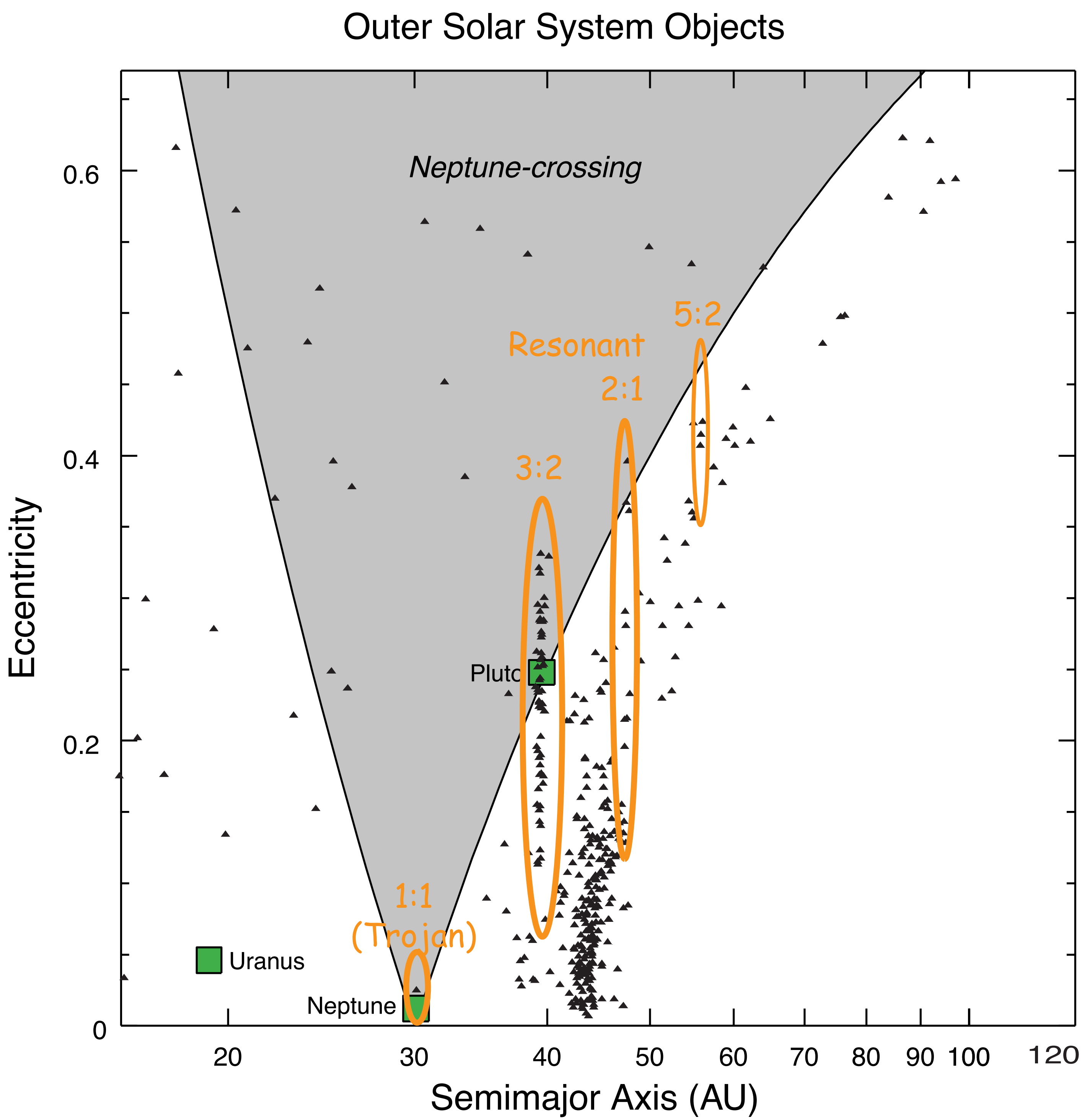


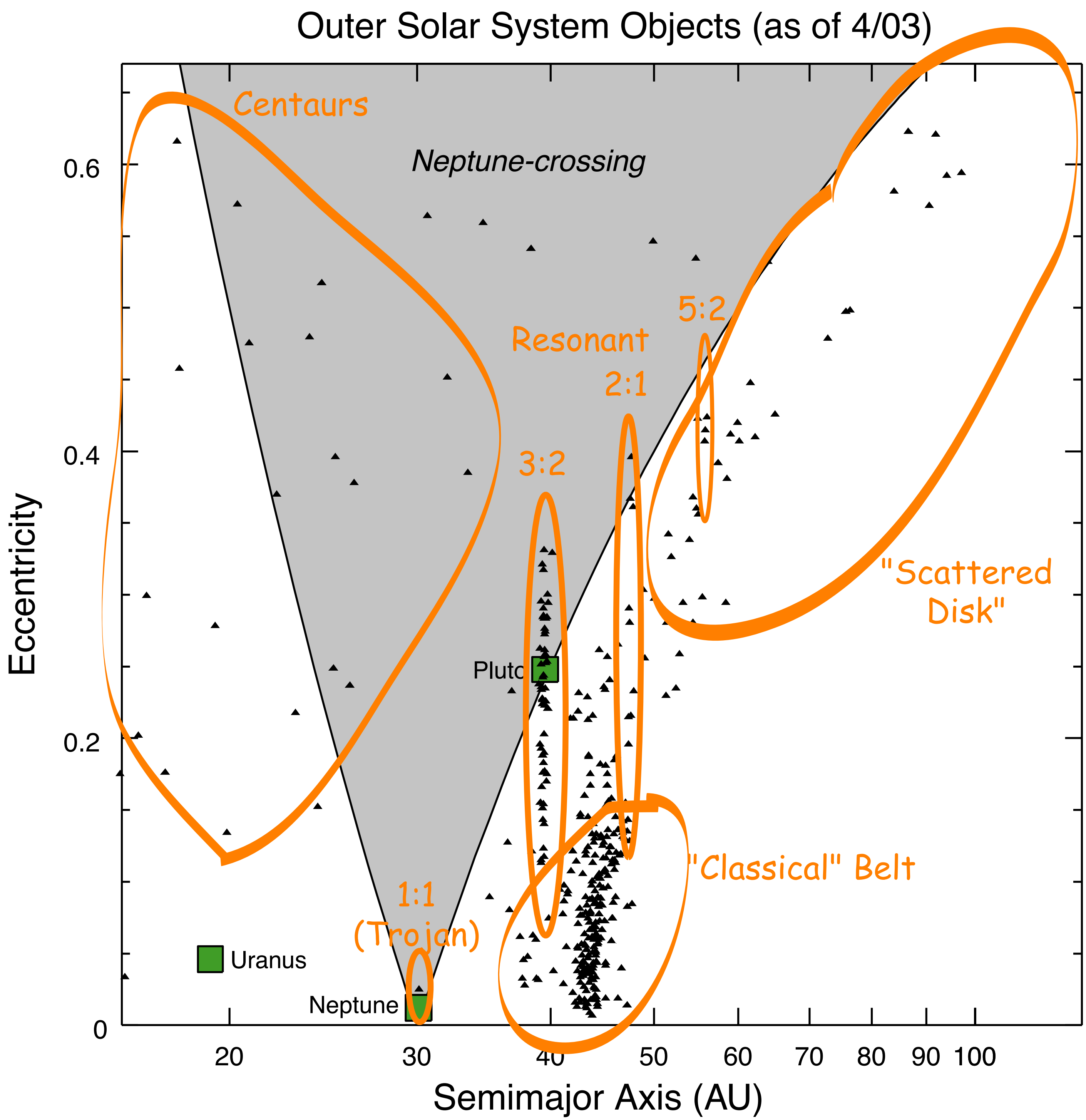
- Malhotra (1993) explains "accident" of Pluto's resonance by positing an outward migration by ~8 AU of Neptune during the clearing of the planetesimal disk. Resonances "sweep" through the population, acting like phase-space traps. Prediction is that many KBOs should be found in 3:2 and 2:1 resonances.

Orbit of 2001 QR322 in Neptune frame (Chiang et al 2003)

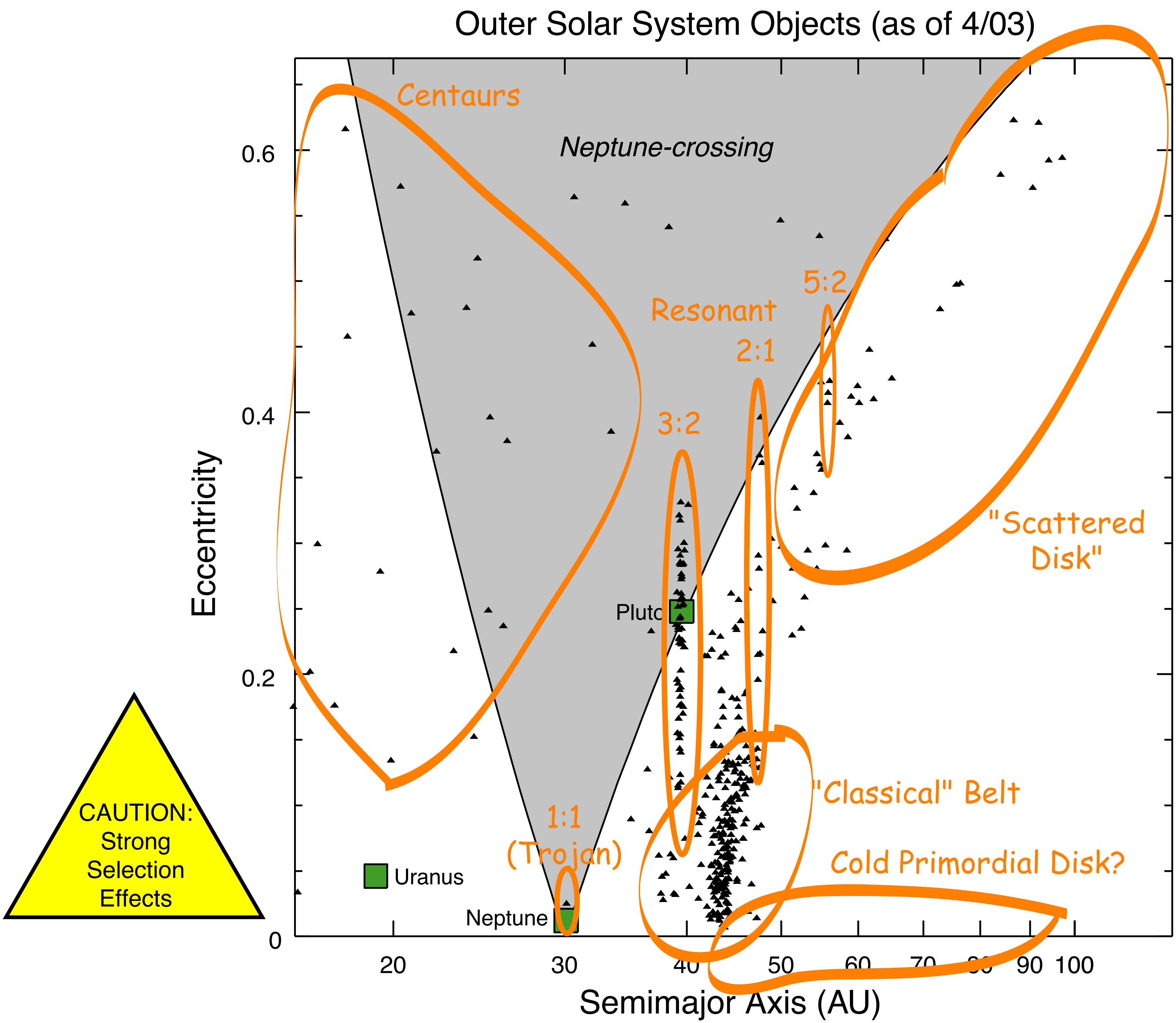


- KBOs have been found in following resonances (Chiang et al '03):
  1:1 ("Trojan"), 5:4, 4:3, 3:2 ("Plutino"), 5:3, 7:4, 2:1, 7:3, 5:2
  Resonance sweeping can only explain some of these, obviously not 1:1. Relative occupancies of these resonances constrains the rate of Neptune migration and the dynamical state of the Kuiper Belt at the time of migration.


Outer Solar System Objects
Neptune-crossing
Resonant
5:2
2:1
3:2
1:1
(Trojan)
Pluto
Uranus
Neptune
Eccentricity
0.6
0.4
0.2
0
20
30
40
50
60
70
80
90
100
120
Semimajor Axis (AU)

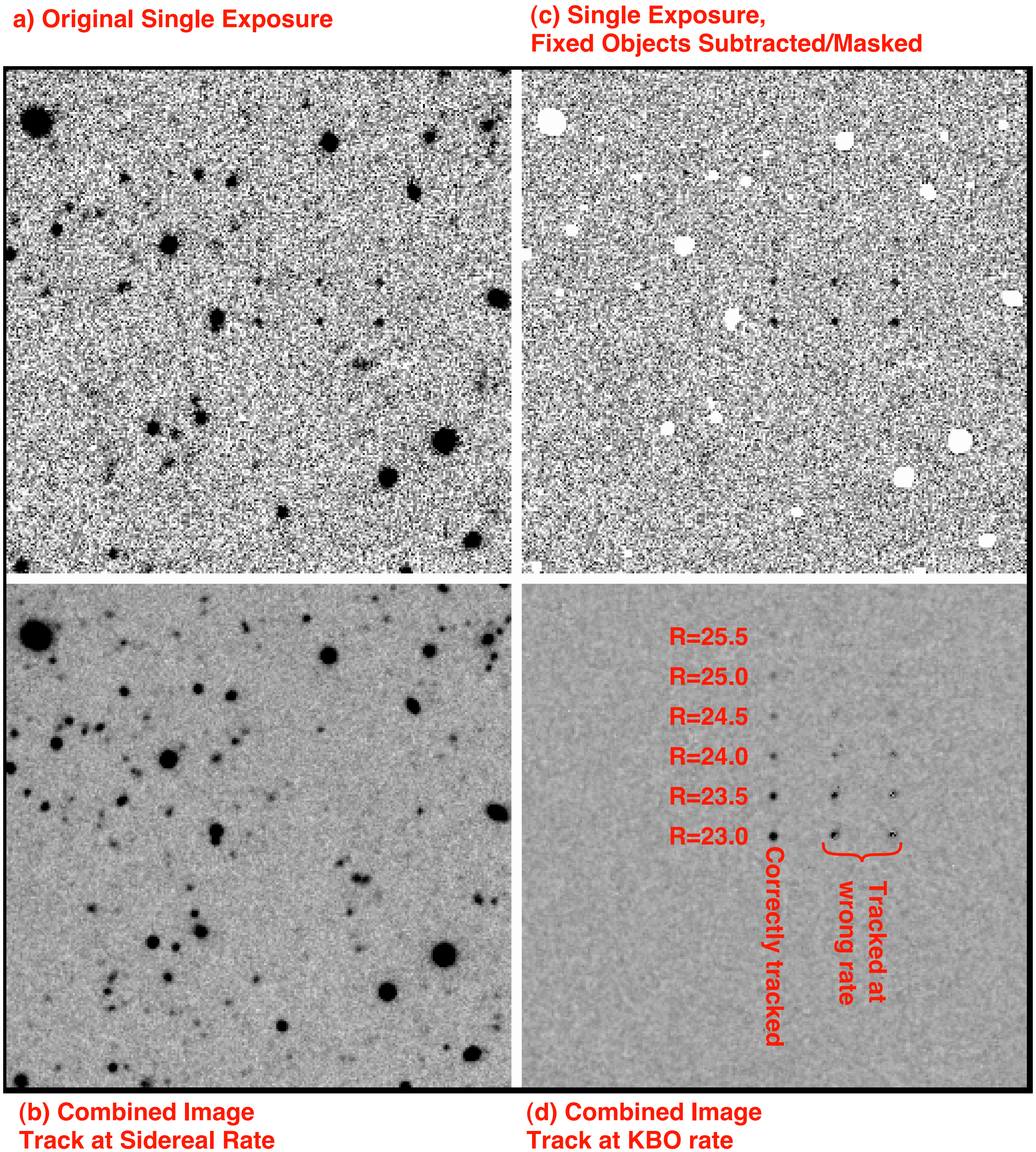


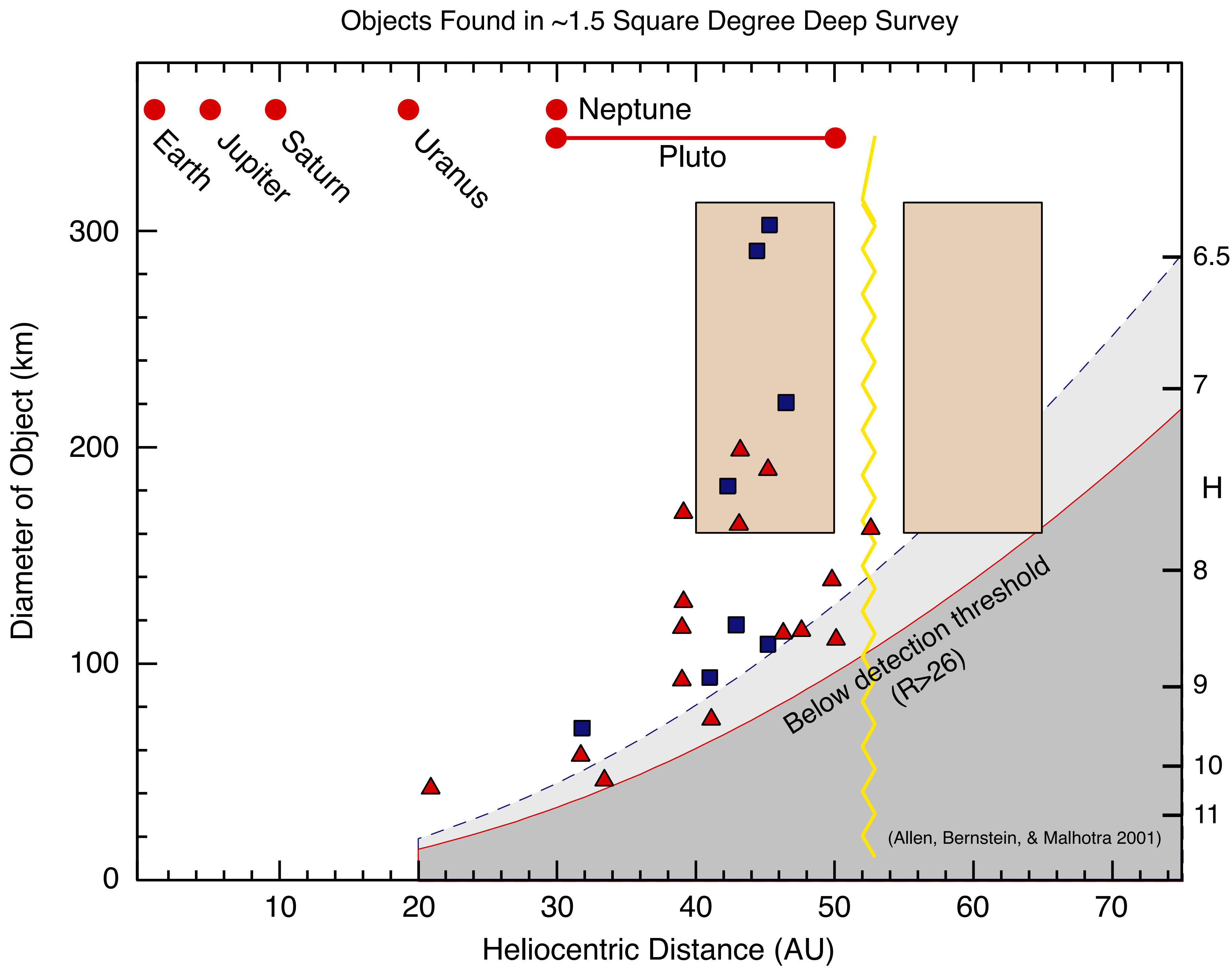
Outer Solar System Objects (as of 4/03)
Centaurs
Neptune-crossing
5:2
Resonant
2:1
3:2
"Scattered Disk"
Pluto
"Classical" Belt
1:1 (Trojan)
Uranus
Neptune
0.6
0.4
0.2
0
20
30
40
50
60
70
80
90
100
Eccentricity
Semimajor Axis (AU)



Outer Solar System Objects (as of 4/03)
Centaurs
Neptune-crossing
Resonant
5:2
2:1
3:2
"Scattered Disk"
Pluto
1:1 (Trojan)
"Classical" Belt
Cold Primordial Disk?
Uranus
Neptune
CAUTION: Strong Selection Effects
Eccentricity
0.6
0.4
0.2
0
20
30
40
50
60
70
80
90
100
Semimajor Axis (AU)

Digital Tracking of a simulated swarm of KBOs in a typical ground-based image:




Objects Found in ~1.5 Square Degree Deep Survey
Earth
Jupiter
Saturn
Uranus
Neptune
Pluto
300
200
100
0
10
20
30
40
50
60
70
Diameter of Object (km)
Heliocentric Distance (AU)
6.5
7
H
8
9
10
11
Below detection threshold
(R>26)
(Allen, Bernstein, & Malhotra 2001)

Major Events Must Have Shaped KBO Dynamics:

- Velocity dispersion (eccentricity & inclinations) of the observed non-resonant are far from being the undisturbed remnants of a dynamically cold primordial disk. Some event(s) and/or process(es) must have excited the orbits.

- Collisions among KBOs in current dynamical state result in ***erosion***, not ***accretion*** (e.g. Stern & Colwell), implying that the large bodies currently seen did not form in the current dynamical environment.

- Several lines of evidence that the Kuiper Belt must have been much more massive than currently seen: necessary to accrete the observed large bodies; extrapolation of density distribution of giant planets; need sufficient mass to drive Neptune migration.

- "Scattered disk objects" (SDOs) have very high ellipticity but perihelion near Neptune. Numerical models show that such orbits can survive multi-billion years (though chaotic). Were they placed on such orbits by scattering from Neptune? If so, how did 2000 CR105 get a=220 AU but perihelion of 44 AU?

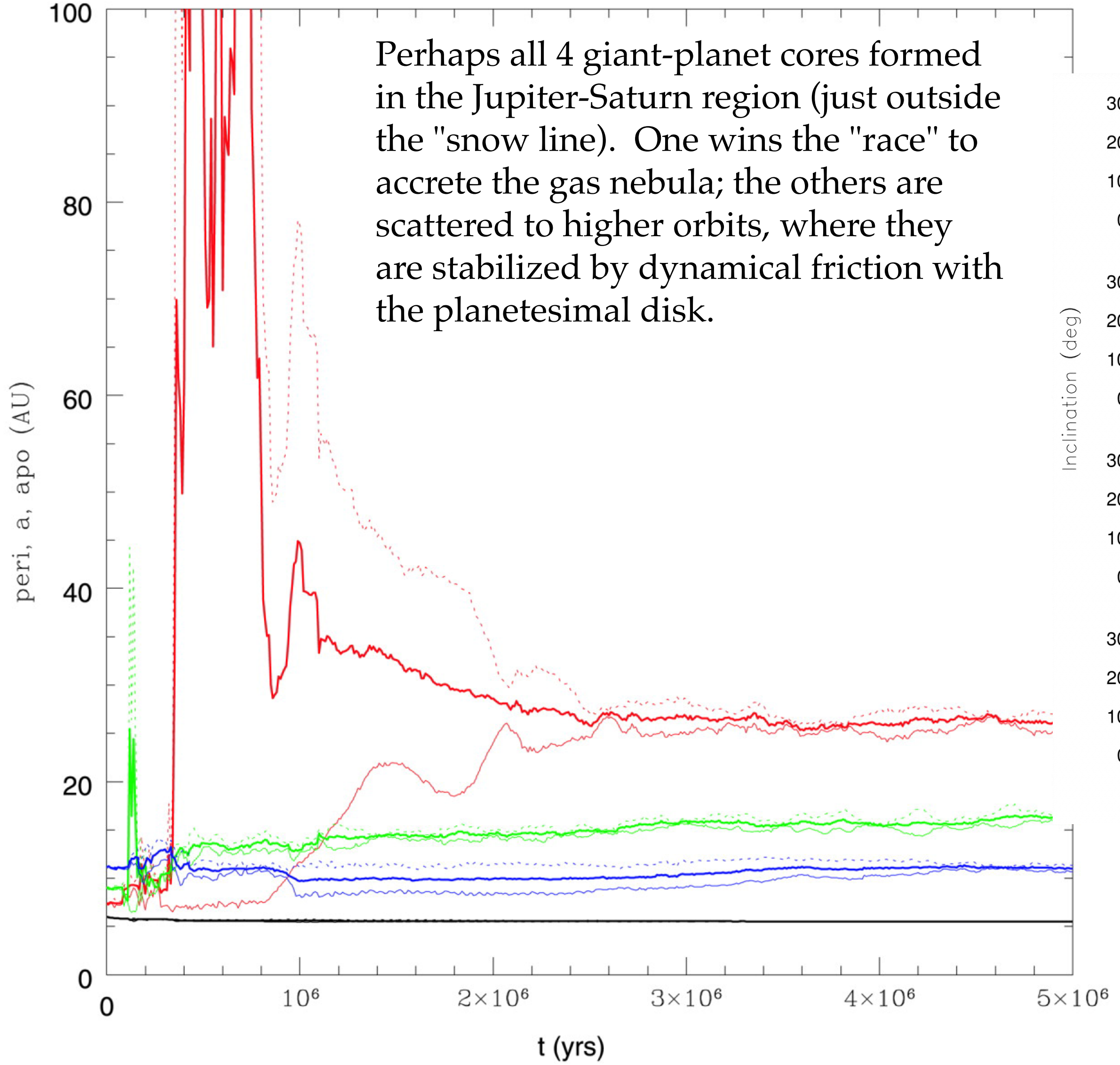
- Some proposed mechanisms for "stirring" the Kuiper Belt and halting the accretion process:
  - Tidal disturbance from a passing star, esp. in Sun's birth cluster (Ida)
  - Temporary residence of Mars-mass "embryos" that were later ejected (Morbidelli &Valsecchi; Petit)
  - Lunar-Martian mass bodies that are ***still*** present on highly eccentric orbits (Fernandez; Ip)
  - Temporary presence of Neptune/Uranus in eccentric orbits (Thommes et al)
  - *All* objects carried beyond 30 AU by Neptune migration (Morbidelli & Levison)

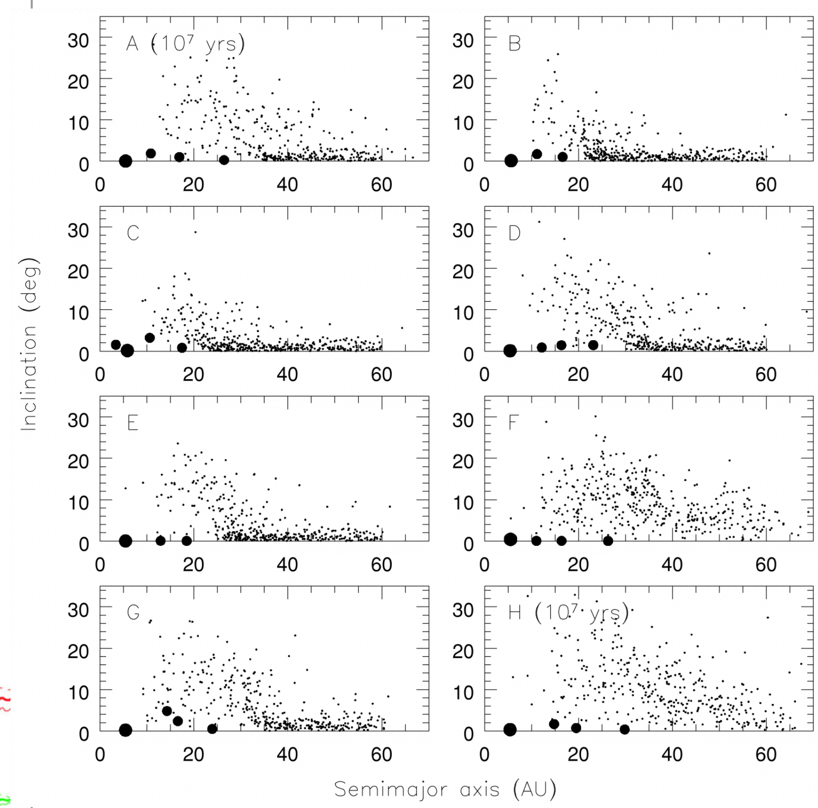
- How did Sedna get into an orbit with perihelion of 80 AU???

An interesting scenario from Thommes, Duncan, & Levison (2002):

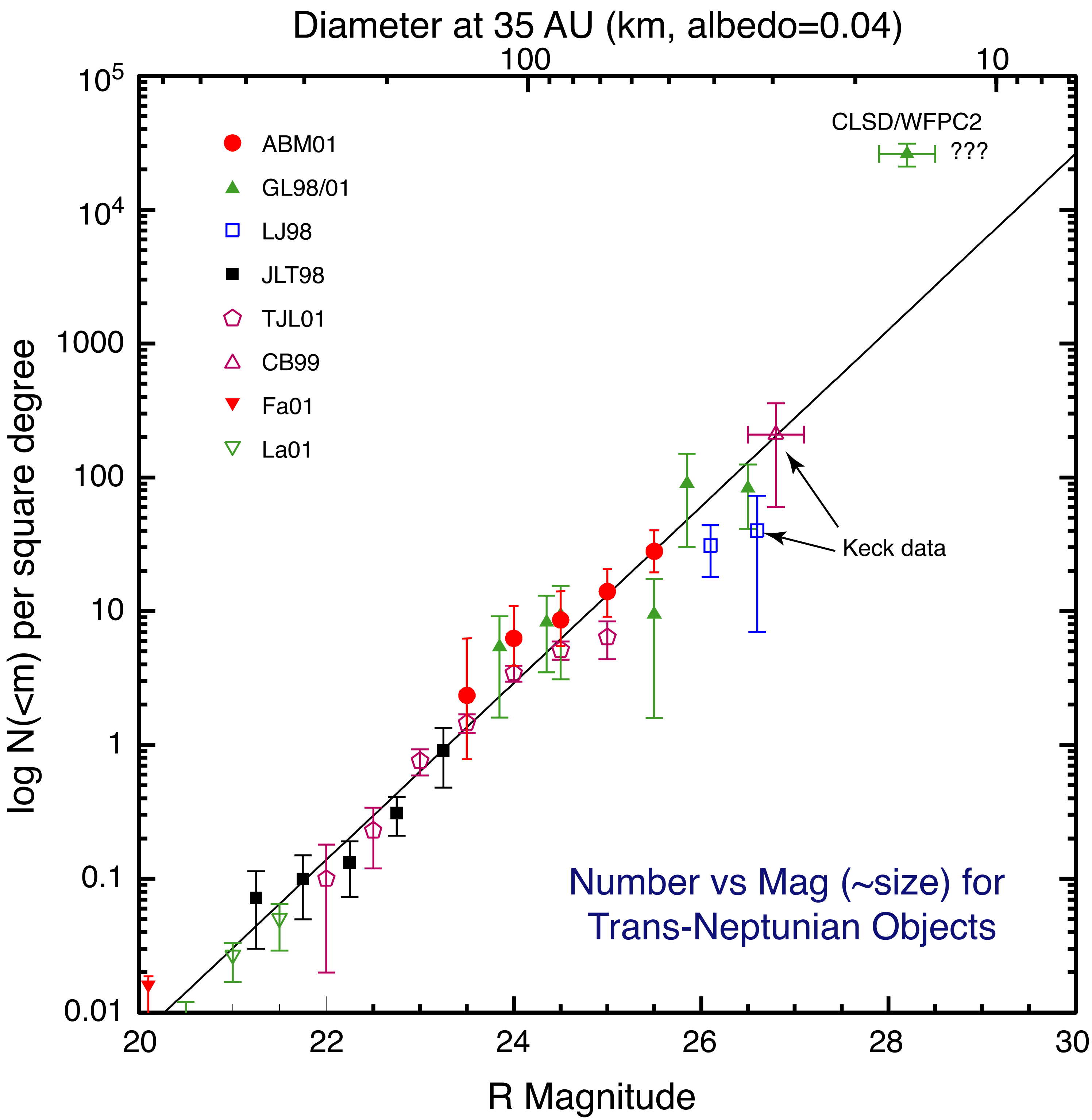
It is difficult to accrete the rocky cores of Neptune & Uranus quickly enough in their present locations.

Perhaps all 4 giant-planet cores formed in the Jupiter-Saturn region (just outside the "snow line). One wins the "race" to accrete the gas nebula; the others are scattered to higher orbits, where they are stabilized by dynamical friction with the planetesimal disk.





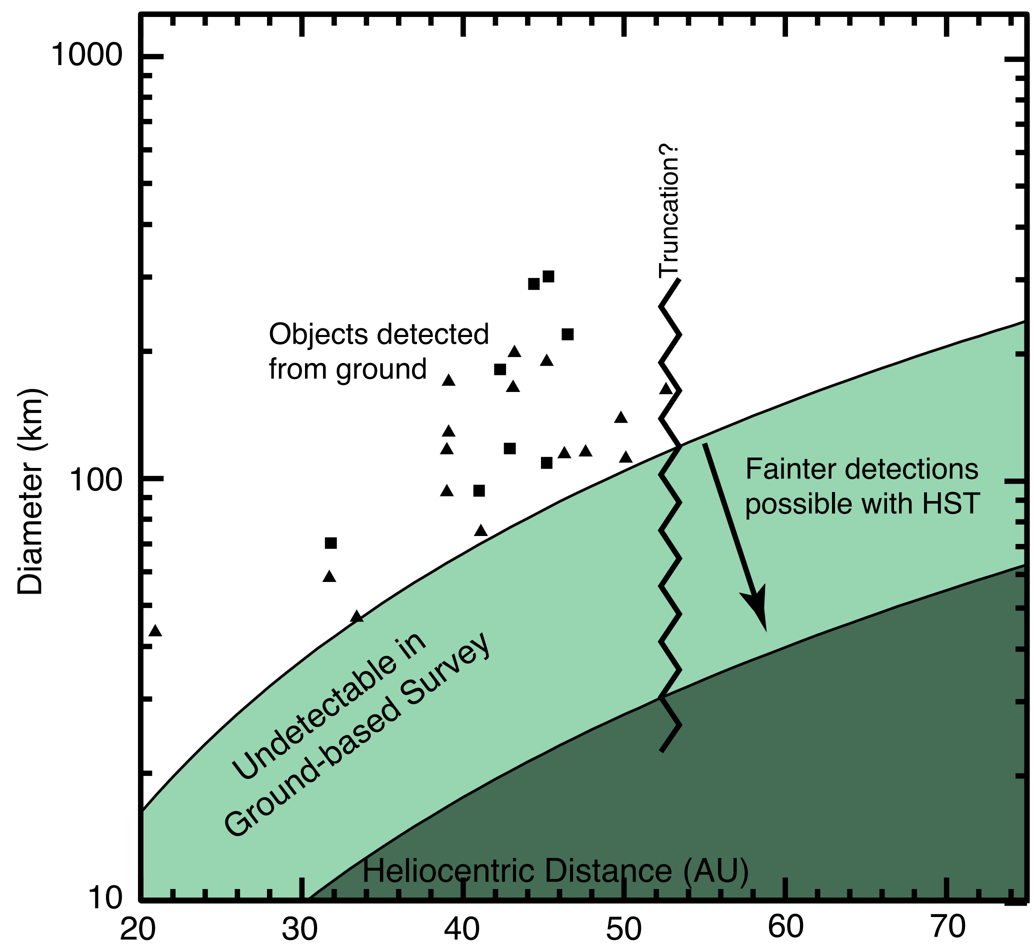
Some of the final configurations resemble excitation of KBO disk, but not truncation.



Diameter at 35 AU (km, albedo=0.04)
100
10
log N(<m) per square degree
R Magnitude
ABM01
GL98/01
LJ98
JLT98
TJL01
CB99
Fa01
La01
CLSD/WFPC2
???
Keck data
Number vs Mag (~size) for
Trans-Neptunian Objects

What Can Space-Based Observations Add to Solar System Knowledge?

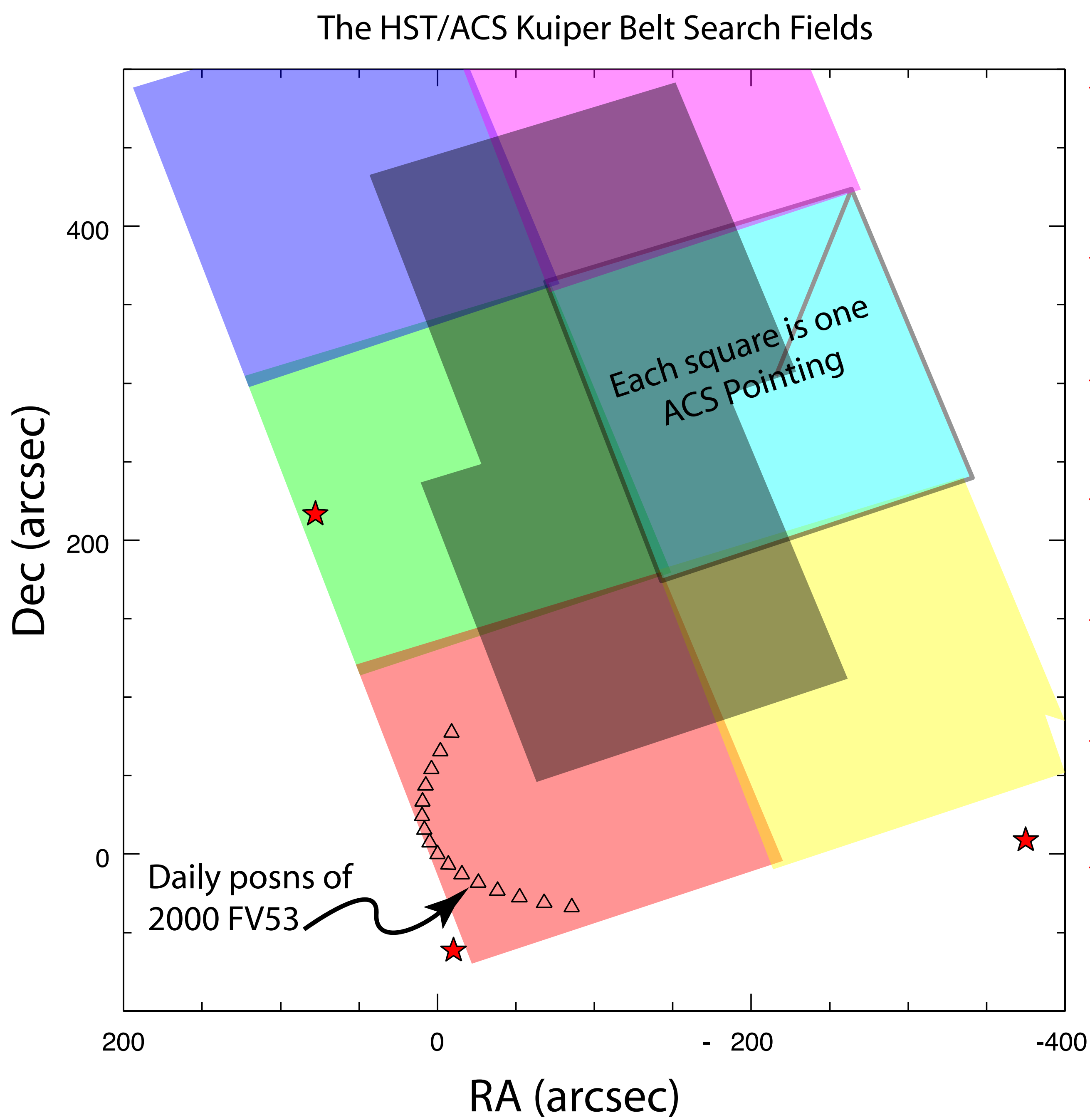
- Faster detection of faint point sources allows ***1-2 mag fainter threshold*** for "blinking" detections or for "digital tracking" detections: fainter and/or more distant bodies.
- Better S/N also enables vast numbers of visible/NIR ***colors***, and ***light curves*** give shape/rotation rate surveys.
- Better resolution enables detection of KBO ***binaries***: angular momentum state of the population is important information.
- Better astrometry and orbits. Easily detect motion of bodies to 10,000 AU in 1 day.
- No scintillation: high-speed photometry enables detection of ***occultations*** in the diffractive limit.



Note that small-body searches usually have specific pointing/timing constraints that make them difficult to piggyback on most Galactic/extragalactic surveys. The converse, however, is much easier: e.g. a 39,000 s ACS image over 0.02 square degrees is a KBO-search byproduct.

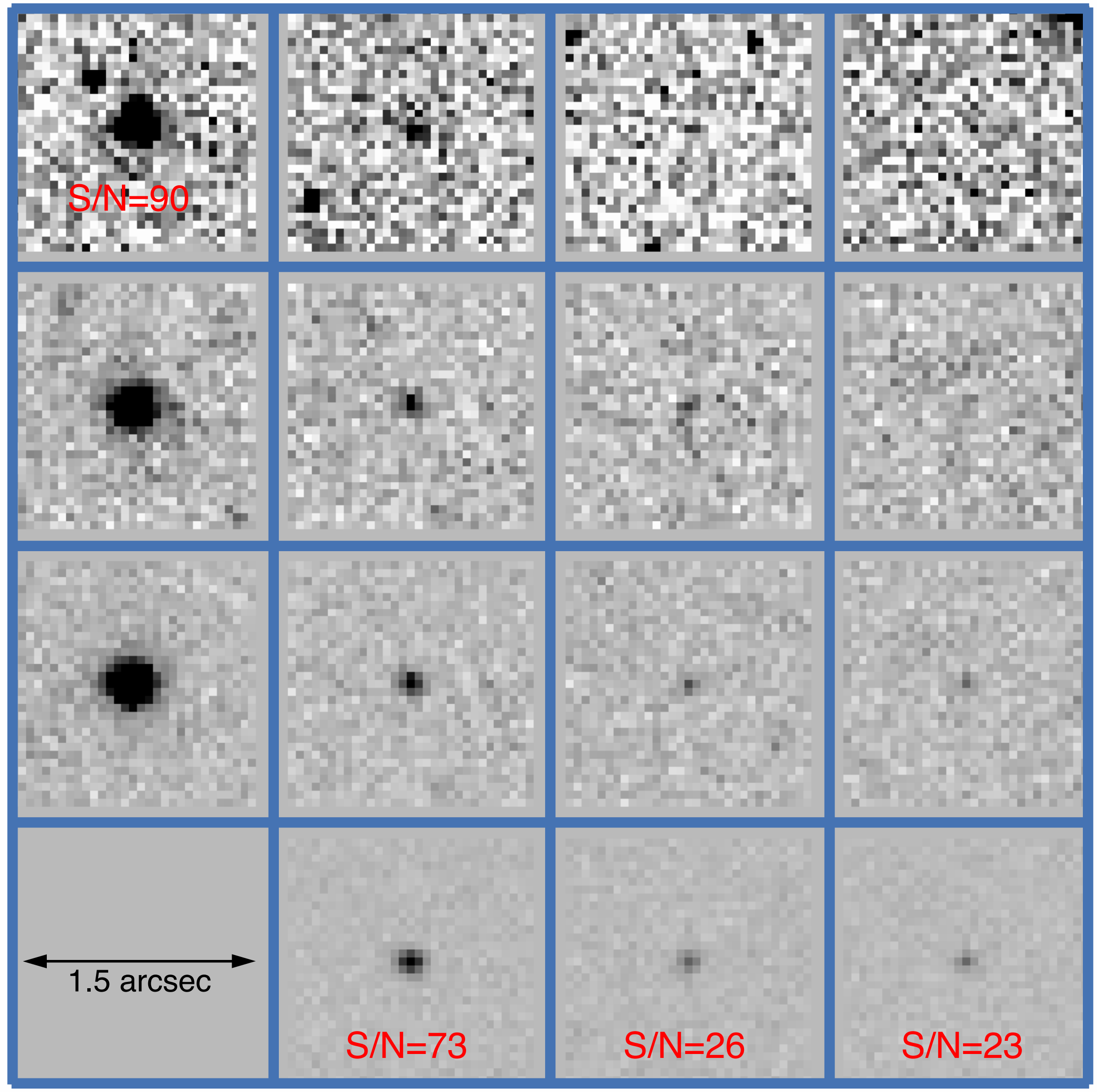
Wide Field of View is Essential for Substantial Progress!

Layout of the ACS TNO Survey



- Six ACS fields, total area 0.02 square degrees (12x area of the Hubble Deep Field.
- Each field observed for 22 ksec over 5-day span.
- Sum flux over each of ~10^{14} candidate TNO orbits.
- Wait 5 days; most TNOs pass stationary points and reverse.
- Observe another 16 ksec per field to confirm discoveries.
- Detection limit: m<29.2 mag in F606W filter.
- Expect ~85 detections under simple extrapolation.

TNOs from the ACS Survey:



Distance:	40.26 AU	42.14 AU	42.55 AU
Inclination:	2.5 deg	1.5 deg	2.0 deg
Eccentricity:	0.07	??	??
Diameter:	44 km	28 km	25 km

Faintest Solar System objects ever detected!
(about 1 photon per 5 seconds at HST)

Sky Density of TNOs from All Surveys:

- Collect survey data within 3 degrees of invariable plane from:

  Trujillo & Brown 2003
  Larsen et al. 2001
  Trujillo, Jewitt, & Luu 2001
  Allen, Bernstein, & Malhotra 2001
  Gladman et al. 2001
  Chiang & Brown 1999
  This ACS Survey.

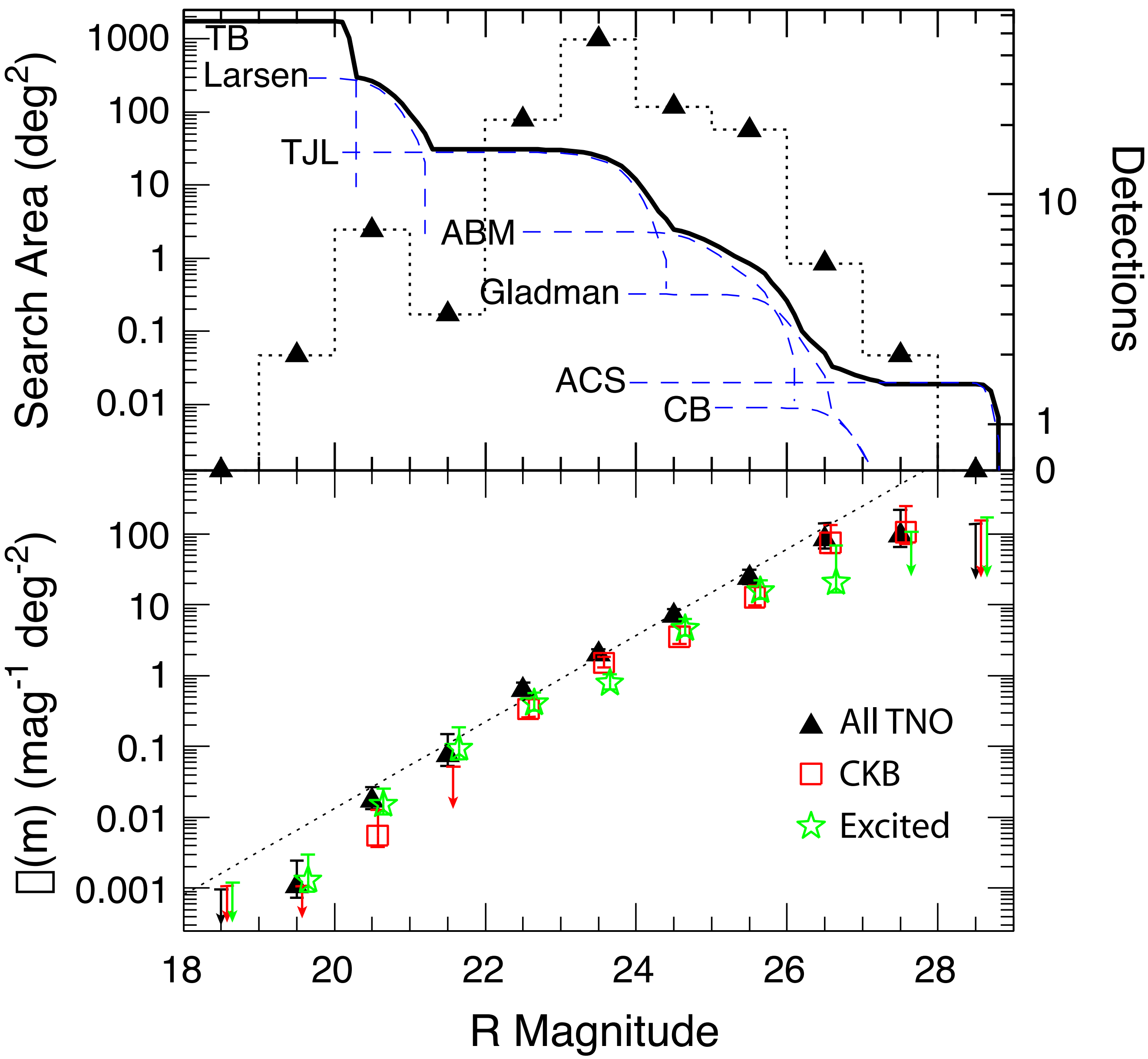
- Divide detections into dynamical classes:

  TNO: d>25 AU

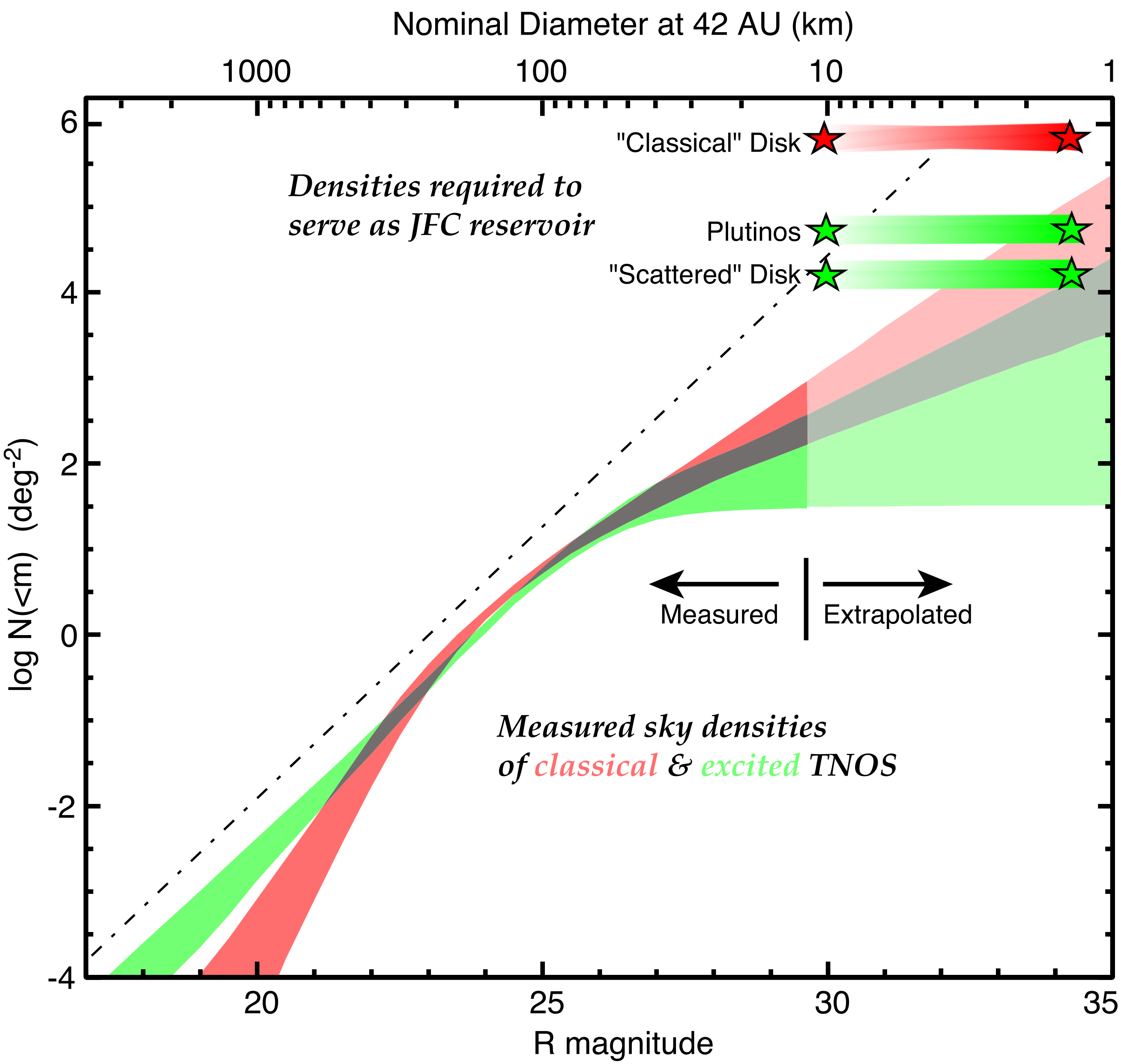
  "Classical" (CKBO): 38 AU < d < 55 AU, i<5 degrees

  "Excited": TNOs - CKBOs

- Data are no longer fit by a single power law. Departures at both faint and bright ends in all dynamical samples.



Can the Kuiper Belt be the source of Jupiter Family Comets?



Dynamical models give rate of transformation of TNOs into JFCs. Are the reservoir populations large enough?

NO - if observed JFCs arise from 10-km TNOs.

Maybe if JFC precursors are 1 km diameter.

An Example Space Survey Program:

SNAP-like instrument at L2 scans near the quadrature points in ecliptic, where apparent motion of KBOs is minimized. ~1 hour integration per point on sky yields detections to m~28. Repeat same patch of sky 6 months later at other quadrature to obtain orbital elements of all bodies.

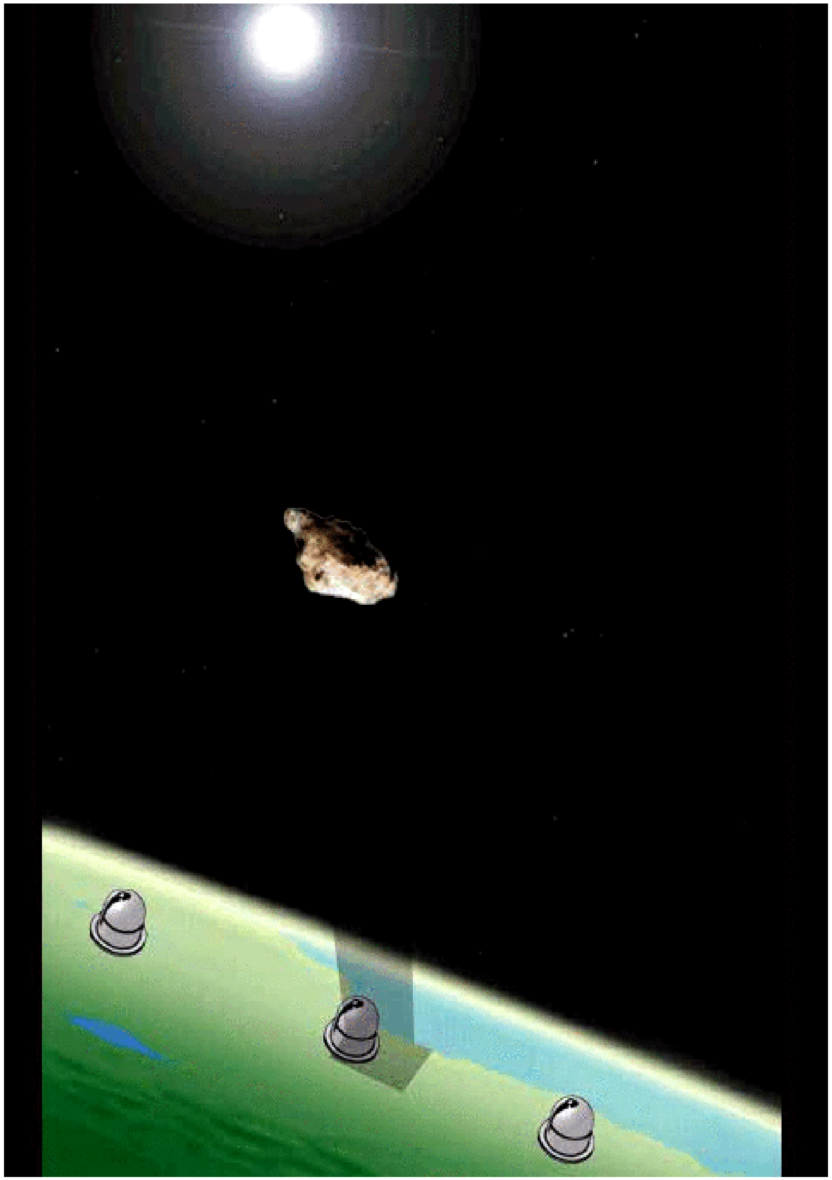
SNAP FOV of 0.5 square degrees means 12 square degrees per day, 360 square degrees per month. Roughly 100 KBOs per square degree near ecliptic at 28th mag, so *36,000 discoveries per month!* (plus another month 6 later).

This would be ~2 mag deeper than likely Pan-STARRS or LSST survey depth, and just this one month's survey would roughly match the total number of (larger) KBOs found in their full-sky surveys. More importantly the size distribution could be studied as function of dynamics.

Accurate colors into NIR for all objects m<25 or so, also track vs dynamics. Automatic binary fraction measurements as well.

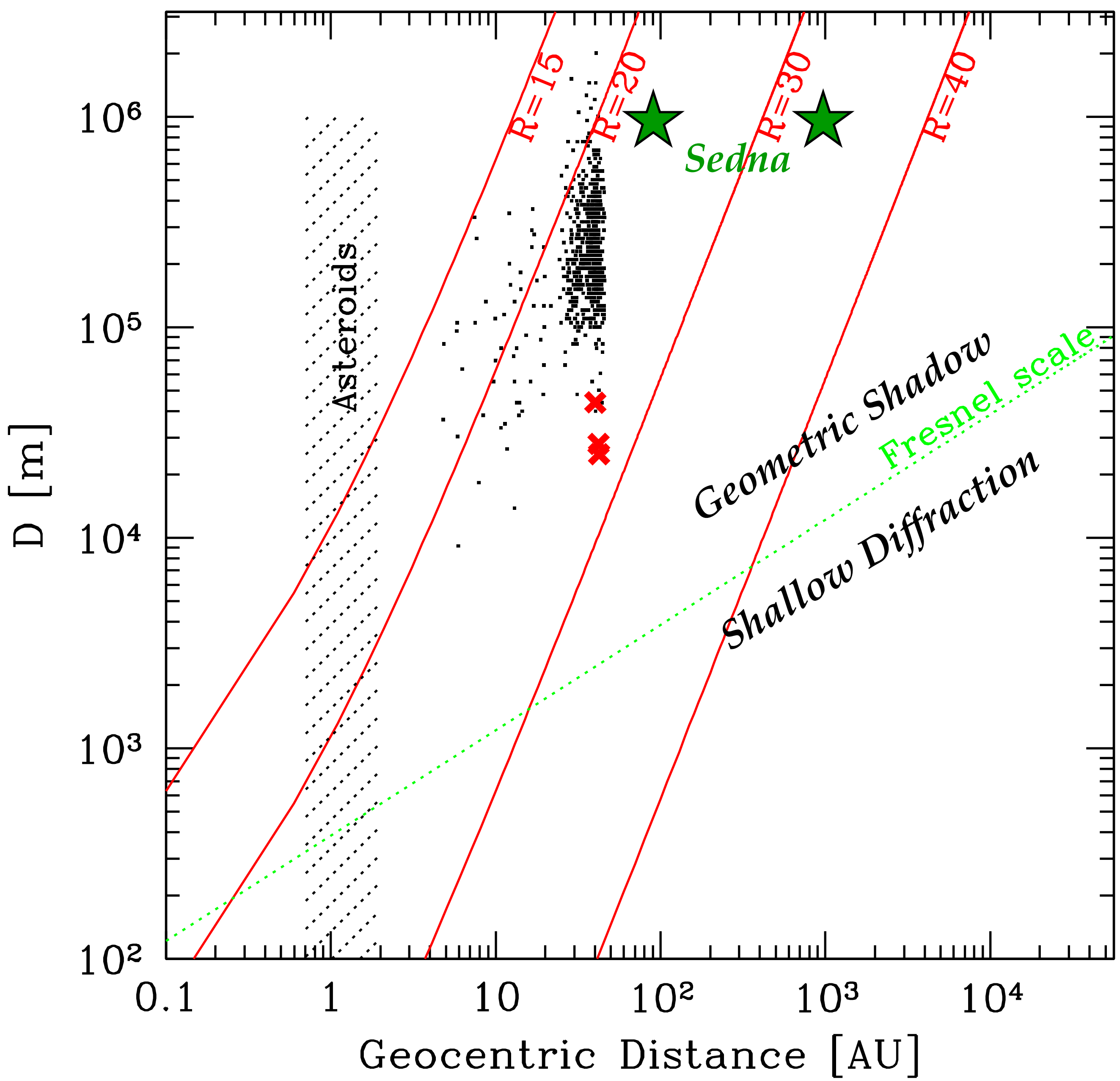
What about "Sednoids"? If size distribution is similar to KBOs, then 1 object at m=21 means there are ~3000 m<27 Sednoids near 80 AU. Sedna itself is visible until it's 350 AU away, space survey should find many times more that are NOT near perihelion. What are the dynamics of this population? Are there even larger objects not currently near perihelion? Scattered planetary embryos?

The Taiwanese-American Occultation Survey (TAOS): A ground-based survey

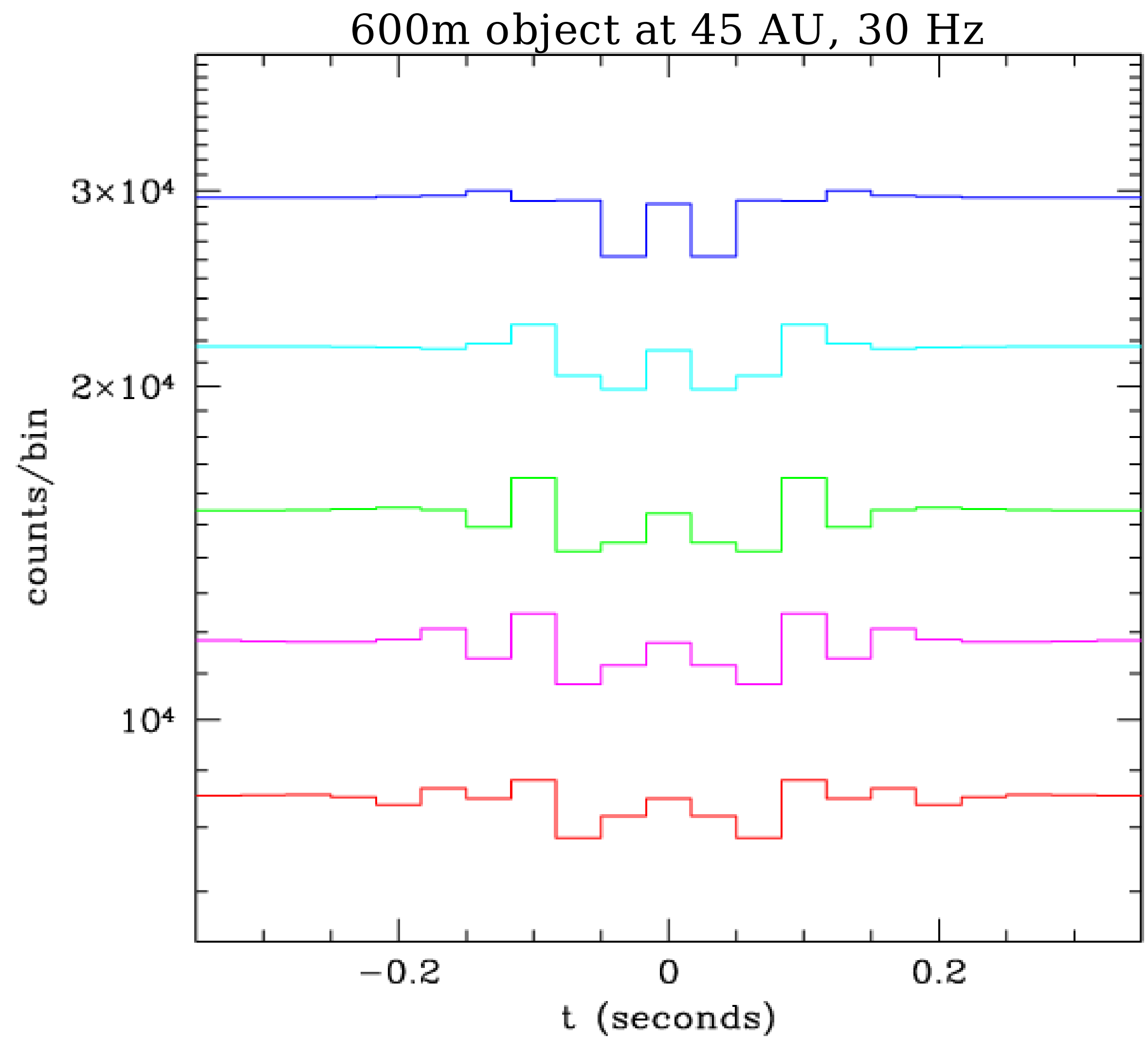


- Samples ~3000 stars at 5 Hz
- Sensitivity:
  ~1km objects at 45 AU
  ~100 km objects at 30,000 AU
- Degeneracy between size, distance, impact parameter
- Expect 10 to 100 events per year when operational (Fall, 2004)

Space Observations Open the Diffraction Regime of Occultations:



1% photometry, fast readout: can resolve very small KBOs



Filter bands:

400 – 500 nm

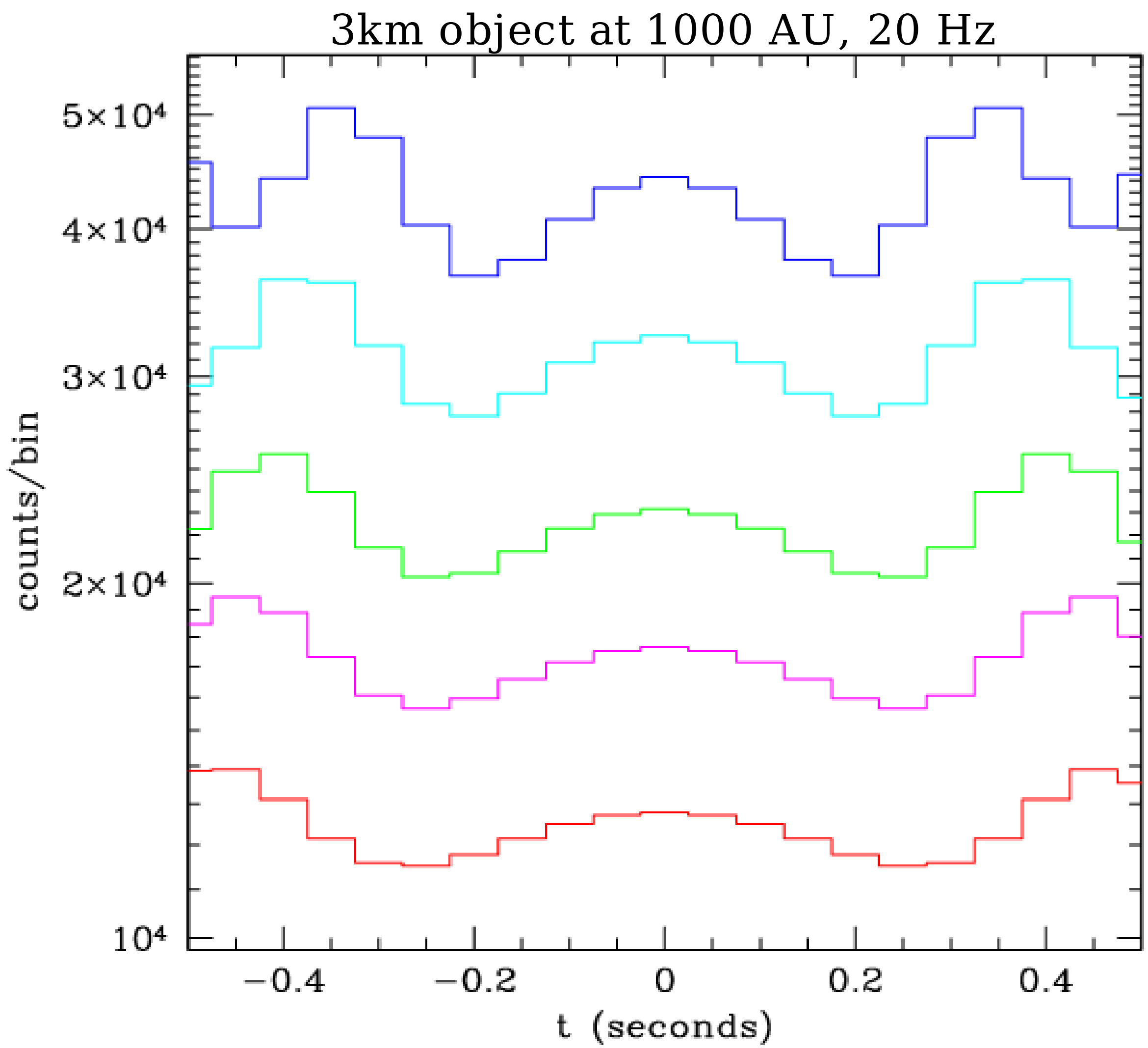
500 – 600 nm

600 – 700 nm

700 – 800 nm

800 – 900 nm

Sensitivity to small objects in Sedna-like orbits



A Space-Based Occultation Search:

"Amphetamine Kepler": Monitor 10,000 stars or so at 30 Hz using CMOS detectors and on-board photometry/alert processing.

Formally sensitive to 3 km bodies at 1-10,000 AU, with sufficiently bright (and small) source star. Event rates are feasible but highly uncertain given the break in size distribution seen by ACS survey, and our total ignorance of the occulting population beyond 50 AU.

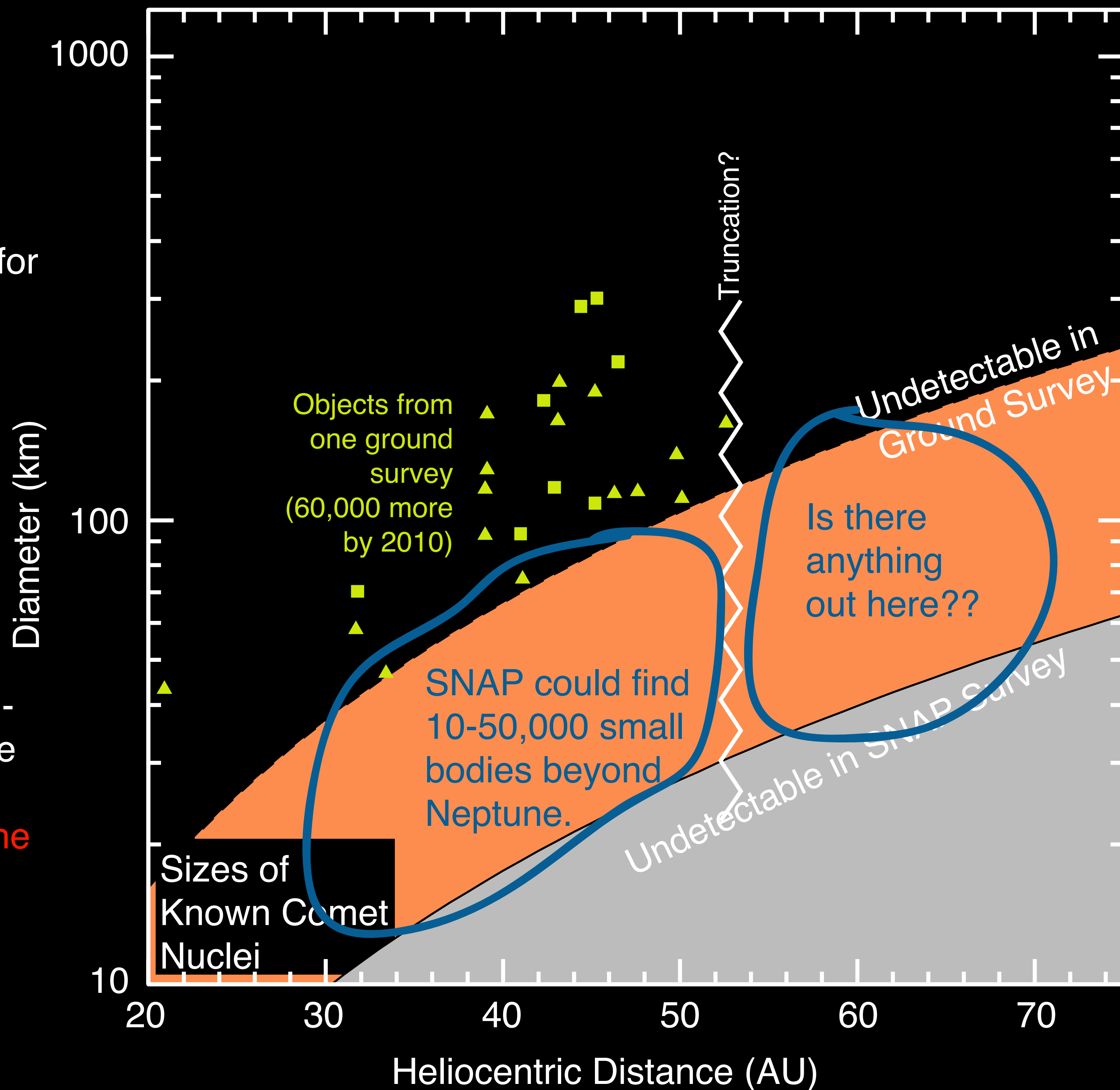
Partial dynamical/size information available from events. Probably the only way to explore the vast majority of the volume available to objects gravitationally bound to the Sun!

TAOS results could demonstrate the technique as soon as 2005.

Kuiper Belt: remnant planetesimals beyond Neptune. Our ONLY chance to view directly a planetesimal system and test accretion theories.

Also the source reservoir for short-period comets.

SNAP can detect fainter (=smaller, more distant) objects than large ground-based surveys will be able to do. In just 2 months, SNAP will obtain 1000x the coverage of an upcoming 120-orbit HST/ACS project.

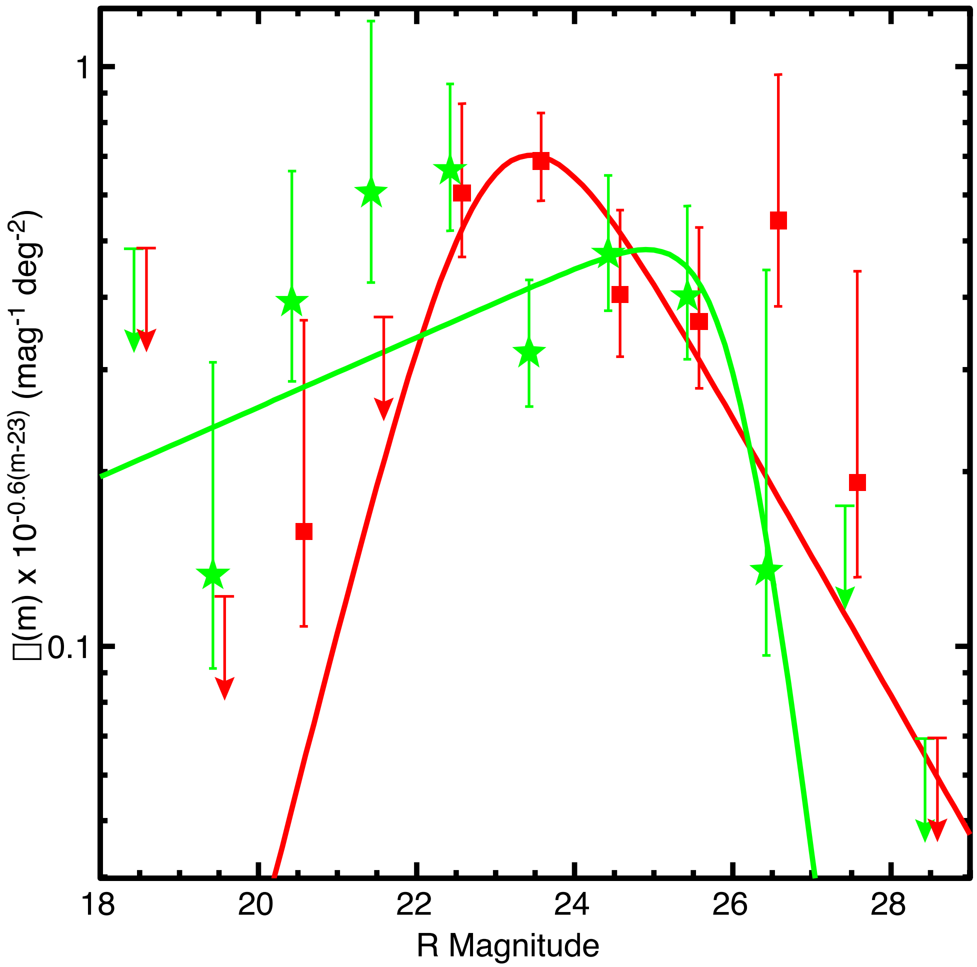


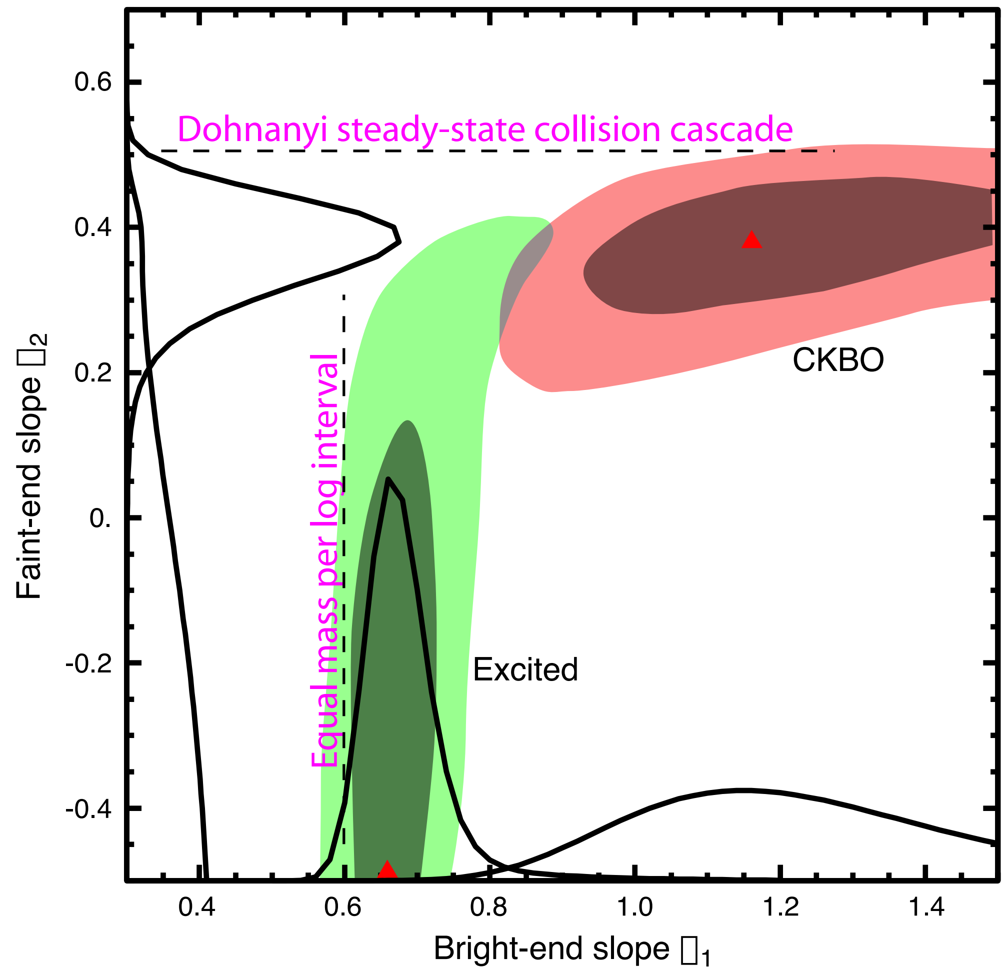
Double Power-Law Fits to the Differential Sky Density:

Likelihood function over 4 parameters:

two slopes, join magnitude, normalization.

Marginalize Bayesian likelihood to get probability distribution of interesting quantities.



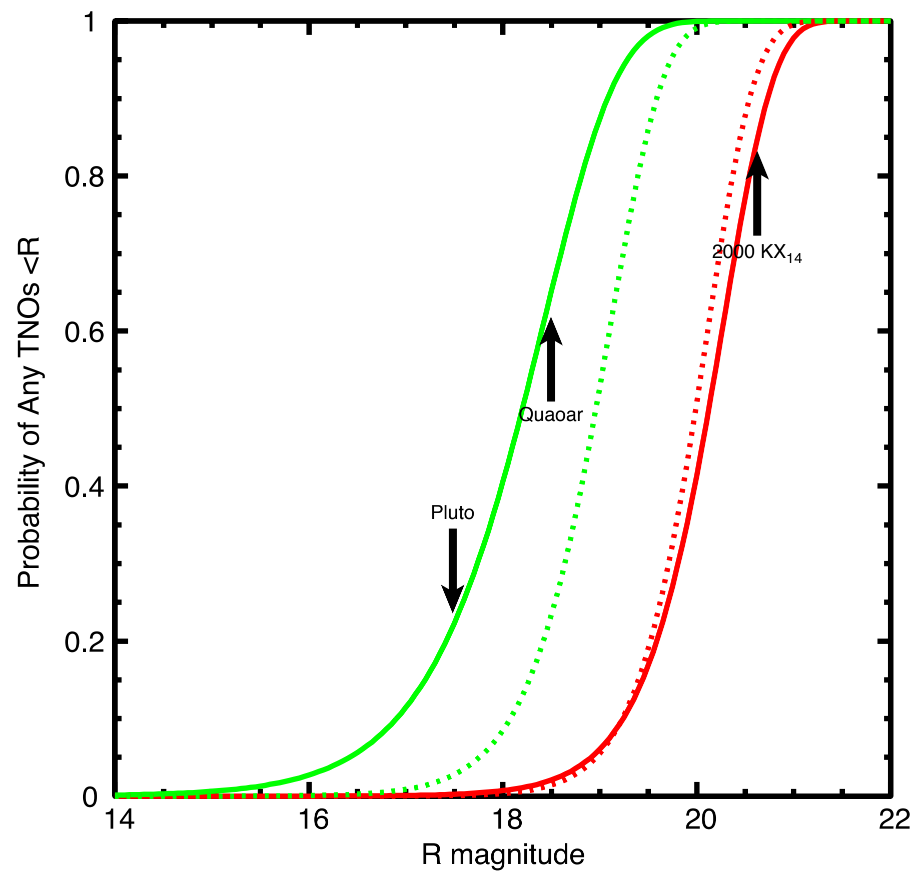


- CKBO and Excited classes differ at 96% CL in KS test.
- Neither class consistent with Dohnanyi steady-state collisional cascade.
- Excited class has shallower bright-end slope => more mass in large objects.
- Excited class has shallower faint-end slope => more advanced erosional depletion?

Some Implications of the New TNO Data

★ ***Total mass of the CKB***: 0.010+-15% M_{Earth} (for p=0.04, <d>=42 AU, =1000 kg/m^3)
Plutinos: similar or lower;
Scattered disk: comparable or few times larger (mean distance poorly known).

★ ***Pluto's relation to KBOs***: extrapolation of bright-end Excited density predicts largest object in range of Pluto/Quaoar. Pluto appears uniquely but not anomalously bright.
Note largest CKBO ~60x less massive.



★ ***The Kuiper Belt beyond 50 AU***: no detections, so any mass at 60 AU in form of >=40 km bodies must be less than the CKB mass. See poster by M. Holman.